Comparative Kinesiology of the Human Body

Normal and Pathological Conditions

Edited by **SALIH ANGIN and IBRAHIM ENGIN ŞIMŞEK**

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Dedication

To my wife Dilayla, my daughters Defne and Diba (my 3Ds) - for their love, support, and sacrifice.

S.A.

. . . and to my wife Tülay, my sons Kuzey ve Rüzgar, for their endless joy and enthusiasm.

İ.E.Ş.

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Contents

List of contributors xv
Foreword xvii
Preface xix
Acknowledgments xxi

Part 1
History and basics of kinesiology

1. Past, present and future of kinesiology 3

Fatma Uygur

Historical perspective of the kinesiology studies 3
Development of kinesiology in modern age 3
Kinesiology in 21st century and beyond 9
References 10

2. Principles of kinesiology 13

Ata Elvan and Seher Ozyurek

Basic information 13
- Introduction to kinesiology 13
- Cardinal plane and axes of motion 13
- Motion 15

Mathematical fundamentals 16
- Units of measure 16
- Scalars and vectors 16
- Scalar quantities 16
- Vector quantities 16
- Vector analysis 16
- Trigonometric functions 17

Kinematics 17
Kinetics 18
- Forces 20
- Resultant force 20
- Types of forces 20
- Gravity 20
- Muscles 21
- Friction 21
- Externally applied resistances 22
- Torque 23
- Center of gravity 23
- Free body diagram 24

Newton’s laws 25
- First law (inertia) 25
- Second law (acceleration and momentum) 25
- Third law (action-reaction) 25

Levers 25
- First class lever 25
- Second class lever 25
- Third class lever 26

Equilibrium 26
References 27

3. Fundamentals of human movement, its control and energetics

Hayri Ertan and Ismail Bayram

How does a purposeful movement start? 29
Neural control mechanisms of reflex and purposeful movements 29
- Central nervous system 30
- Peripheral nervous system 31
- Motor systems 34

Energetics in human movement 35
- Metabolic and mechanical energy sources of terrestrial movement 36
- Energetics and mechanics of terrestrial locomotion 36
- Comparison of bipedal and quadrupedal locomotion 37
- Mechanical and metabolic energy cost of walking and running 39
- Measurement methods of energy consumption 39

Doubly labeled water (DLW) method 40
Direct calorimetry 41
Indirect calorimetry 41
Conclusion 42
References 43

4. Architecture of human joints and their movement

Yavuz Yakut and Ayşenur Tuncer

Classification of joints 47
- Joint complexity 47

- Functional classification of joints 47
- Structural classification of joints 47
- Planes of movement and axis of rotation in synovial joints 50
- Degree of freedom 51
- Synovial joint sub-classification 51

Osteokinematics and arthrokinematics 52
- Convex and concave rules 52
- Open and closed kinematic chains 53
- Joint congruency 53
- Congruous—incongruous relationships of joints 54

Patho-architecture of joints 55
- Diseases of joints 56

References 56

Part 2
Tissues

5. Morphogenesis and biomechanics of the human embryo and fetus

Sevil Köse, Bariş Baykal, Feza Korkusuz and Petek Korkusuz

Embryologic development 61
- Development of muscloskeletal system 61
- Molecular mechanisms of muscloskeletal development 63

Biomechanics of human uterus, embryo and fetus 66
- Mechanical features 66
- Measuring mechanical features of the embryo and fetus 66

References 67

6. Architecture of bone tissue and its adaptation to pathological conditions

Elif Bilgiç, Özge Boyacıoğlu, Merve Gizer, Petek Korkusuz and Feza Korkusuz

Introduction 71

Macroscopic Bone Types 71
- Cortical (Compact) Bone 71
- Trabecular (Spongy) Bone 71

Microstructure of the Bone 72
- Bone architecture 72
- Gross Anatomy of Bone 73
- Composition of the bone tissue 74

Mechanical Properties of Bone 77
- Bone as a composite natural material 77
- Biomechanical behavior of bone 78
- Bone behavior under different loading situations 78

Bone tissue in different life stages 82
- Development of bone tissue 82

Adaptation of the bone tissue to pathological conditions 84
- Apoptotic response by bone cells 84
- Osteoclastogenesis 84
- Angiogenesis 85
- Osteolysis and mineralization 85
- Bone formation 85
- Clinical approaches 85

Conclusion 87

References 87

7. Architecture of cartilage tissue and its adaptation to pathological conditions

Mehmet Selcuk Şenol and Hamza Özer

Introduction 91

Microstructure of the cartilage 91
- Layers 91
- Matrix regions 93

Mechanical properties of the cartilage 94
- Theories and the fluid flow 95

Cartilage tissue in different life stages 96

Adaptation of the cartilage to pathological conditions 97

References 98

8. Architecture of muscle tissue and its adaptation to pathological conditions

Tüzün Firat

Introduction 101

Microstructure of the muscle tissue 101

Basic architectural definitions 104

Mechanical properties of the muscle 105
- Muscles of the upper limb 106
- Muscles of the lower limb 106
- Muscles of the shoulder 107
- Muscles of the trunk 107
- Muscles of the pelvic floor 107

Muscle tissue in different life stages 108
- Effect of aging 108
- Effect of childhood 108

Architectural adaptation of the muscle to pathological conditions 108
- Denervation 108
- Spasticity 108
- Immobilization 109

Muscle architecture based planning in rehabilitation approaches 109
- Stretching 109
- Strengthening 110
- Neuromuscular electrical stimulation 110
- Tendon transfers 111

Conclusion 111

References 111

9. Architecture of tendon and ligament and their adaptation to pathological conditions

Derya Özer Kaya

Introduction 115
Architecture of tendons 115
  Structure 115
  Composition and biochemical constituents 117
  Function 117
  Biomechanics and mechanical properties 118
  Vascular supply 120
  Neural structures 121
  Summary of tendon architecture 121
Tendon response to loading, injury, and healing 121
  Physiological responses to mechanical loading and injury 121
  Mechanical loading and adaptation concept 121
  Tendon injury and pathology 124
  Tendon healing 127
  Optimal loading and rehabilitation 130
Architecture of ligaments 132
  Structure 132
  Composition and biochemical constituents 132
  Function 132
  Biomechanics and material properties 133
  Vascular supply 133
  Neural structures 133
  Summary of ligament architecture 134
Ligament response to loading, injury, and healing 134
  Response to mechanical loading and injury 134
  Ligament healing 135
  Optimal loading and rehabilitation 136
Comparison of tendons and ligaments 137
Affecting factors for the architectures of tendons and ligaments 138
  Aging 138
  Gender and hormones 139
  Immobilization, disuse and exercise effects 140
  Obesity 141
  Diabetes mellitus 141
  Hypercholesterolemia 141
  Hyperuricemia 141
  Renal disease 141
  Connective tissue disorders 142
  Pharmacologic agents 142
  Reconstruction and tissue engineering 142
Conclusion 142
Acknowledgments 143
References 143
Further reading 147

10. Architecture of fascia and its adaptation to pathological conditions

Çetin Sayaca, Mahmut Çalik, Filiz Eyüboğlu and Defne Kaya

Introduction 149
Fascia 149
  Biomechanics of fascia 150
  Function of fascia 150
  Effect of fascia on emotion 150
  Effect of surgery on fascia 151
  The role of fascia in proprioception 151
Fascial pathologies 152
  Hypermobility 152
  The plantar fasciitis 152
  Frozen shoulder 152
  Diabetic foot 152
  Trigger points 153
References 153

Part 3
Upper extremity

11. Kinesiology of the shoulder complex

Sevgi Sevi Yeşilyaprak

Introduction 157
Bones of the shoulder complex 157
  Clavicle 157
  Scapula 157
  Proximal-mid humerus 159
  Sternum 160
Joints of shoulder complex 160
  Sternoclavicular joint 160
  Acromioclavicular joint 162
  Scapulothoracic joint 163
  Glenohumeral joint 167
Muscles of shoulder complex 174
  Proximal stabilizers 174
  Distal mobilizers 179
References 185

12. Kinesiology of the elbow complex

Egemen Ayhan and Çiğdem Ayhan

Introduction 191
Anatomy 191
  Surface anatomy 191
Osteology 191

- Humerus 191
- Ulna 192
- Radius 192

Arthrology 192
- Articulations 192
- Articular capsule 192
- Medial collateral ligament 193
- Lateral collateral ligament complex 193
- The forearm and interosseous membrane 194

Kinematics 195
- Flexion and extension 196
- Pronation and supination 196

Muscles 197
- The biceps brachii 197
- The brachialis 198
- The brachioradialis 198
- The pronator teres 198
- The triceps brachii 198
- Tha anconeus muscle 198
- The supinator muscle 198

Stability 199

Instability 202

Elbow kinesiology in acute traumatic injuries 203
- Elbow simple dislocations 203
- Elbow fracture dislocations 203

Elbow trauma and its sequela 204
- Stiffness 204

Elbow injuries in the athlete 204

Medial elbow pain 205
- Flexor-pronator muscle injuries and medial epicondylitis 205
- Ulnar neuropathy 205
- Medial collateral ligament injury 206

Lateral elbow pain 206
- Osteochondritis dissecans of capitellum 206
- Lateral epicondylitis and radial tunnel syndrome 206

Posterior elbow pain 207
- Posterior olecranon impingement 207
- Olecranon stress fracture 207
- Olecranon bursitis 207
- Triceps tendon rupture 207

Anterior elbow pain 207
- Biceps tendon injuries 207
- Median nerve compression 207

Abbreviations 207

References 207

13. Kinesiology of the wrist and the hand

Çiğdem Ayhan and Egemen Ayhan

Kinesiology of the wrist

Introduction 211

Osteology 211
- Distal radius 211
- Distal ulna 212
- Carpal bones 213
- Sesamoid bones 220

Artrology 220
- Wrist joint structure 220
- Articulations 221
- Ligaments 223
- Carpal kinematics 228
- Carpal motions during wrist movements 231
- Muscles 233
- Kinesiology in various carpal conditions 235

Introduction 236

Osteology 238
- Metacarpals 238
- Phalanges 239

Artrology 240
- Carpometacarpal joints 240
- First carpometacarpal joint kinematics 243
- Muscles 248
- Kinematics 252
- Interphalangeal joints of the fingers 253
- Flexor tendon zones 259
- Digital flexor sheath and pulley system 260
- Biomechanical properties of flexor tendons 262
- Extensor system 263
- Intrinsic muscles 271

References 275

Part 4
Trunk and pelvis

14. Kinesiology of the temporomandibular joint

Ayşenur Tuncer

Introduction 285

Structure of the temporomandibular joint 285
- Mandibular fossa 285
- Mandibular condyle 285
- Articular disc 286
- Capsules 286
- Ligaments 287
- Muscles 287
- Innervation 289

Kinematics of the temporomandibular joint 289
- Osteokinematics 289
- Arthrokinematics 290

Kinetics of the temporomandibular joint 293
- Muscle activation and stabilization of the TMJ 293
- Mechanical loading in the TMJ 294
- Mechanical loading in the articular disc 294

Pathomechanics of the temporomandibular joint 295
- TMDs related to muscle disorders 295

  TMDs related to disc derangements 296
  TMDs related to TMJ arthralgia, arthritis, and arthrosis 298
References 299

15. Kinesiology of the cervical vertebral column

Ömer Akçali, Ismail Safa Satoglu and Mehmet Alphan Çakiroğlu

Introduction 303
Functional anatomy 303
Kinesiology of the normal cervical vertebral column 305
  Kinematics of cervical vertebral column 305
  Kinetics of cervical vertebral column 308
  Instantaneous axis of rotation 309
Cervical vertebral column in pathological conditions 310
References 314

16. Kinesiology of the thoracic vertebral column

Ömer Akçali, Ismail Safa Satoglu and Mehmet Alphan Çakiroğlu

Introduction 315
Functional anatomy 315
Kinesiology of the thoracic vertebral column 317
  Kinematics of thoracic vertebral column 317
  Kinetics of thoracic vertebral column 319
  Instantaneous axis of rotation 320
Thoracic vertebral column in pathological conditions 321
References 322

17. Kinesiology of the lumbar vertebral column

Ömer Akçali, Ismail Safa Satoglu and Mehmet Alphan Çakiroğlu

Introduction 325
Functional anatomy 325
Kinesiology of the lumbar vertebral column 326
  Kinematics of lumbar vertebral column 326
  Kinetics of lumbar vertebral column 331
  Instantaneous axis of rotation 334
Lumbar vertebral column in pathological conditions 334
References 336

18. Kinesiology of the pelvis

Çetin Sayaca, Filiz Eyüboğlu, Lacin Naz Tascilar, Mahmut Çalık and Defne Kaya

Introduction 339
Bones of the pelvis 340
  Ilium 340
  Pubis 340
  Ischium 340
  Acetabulum 341
Pelvis-related joints 341
  Sacroiliac joint 342
  The symphysis pubis 342
  The hip joint 343
  The lumbosacral joint 343
Motions of pelvis on the femur 344
  Movements in the sagittal plane 344
  Movements in the frontal plane 344
  Movements in the horizontal plane 345
  Lumbopelvic rhythm 345
  Movements of sacroiliac joint 345
Pelvic motion during human gait 345
Femoral movements on the pelvis 346
Pelvic pathomechanics in specific orthopedic conditions 346
  Pelvic fractures 346
  External fixation 346
  Acetabular fractures 347
  Acetabular dysplasia 347
  Sacroiliac joint dysfunction (SIJD) 347
  Spondylolysis and spondylolisthesis in the lumbosacral joint 348
  Osteitis pubis 348
References 348

Part 5
Cardiorespiratory system

19. Kinesiology of respiration

Deniz Inal-Ince and Aslihan Cakmak

Introduction 353
Structure of thorax and lungs 353
  Conducting airways and the alveoli 353
  Lungs 354
  Thoracic cage 355
  Muscular actions during ventilation 356
  Work of breathing 358
  Mechanics of the respiration 358
Respiratory system in different life stages: newborn, child, adult, and elderly 359
Pathomechanics of the respiration 360

Obstructive lung diseases 361
Restrictive lung dysfunction 361
Acknowledgments 362
References 362

20. Biomechanics of circulation

Abidin Cenk Erdal and Tuğra Gençpinar

Biomechanics of circulation 365
Biomechanics of heart as a pumping device 365
Biomechanics of blood flow in arteries and veins 368
Biomechanics of blood flow in lungs 370
References 371

Part 6
Lower extremity

21. Kinesiology of the hip

Filiz Eyüboğlu, Çetin Sayaca, Mahmut Çalik, Duygu Korkem, Lacin Naz Tascilar and Defne Kaya

Introduction 375
Acetabulum 375
Femoral head and neck 376
Ligamets of the hip joint 376
  Ligamentum teres (foveal ligament) 376
  Iliofemoral ligament 376
  Ischiofemoral ligament 377
  Pubofemoral ligament 377
Muscle dynamics 377
  Piriformis muscle 377
  Quadratus femoris muscle 378
  Obturator internus muscle 378
  Obturator externus muscle 378
  Psoas major muscle 378
  Iliacus muscle 379
  Gluteus minimus muscle 379
  Gluteus medius muscle 379
  Tensor fascia lata muscle 379
  Gluteus maximus muscle 379
Hip joint biomechanics 380
Movements of the hip joint 380
  Femoral movements on the pelvis 381
  Pelvis movements on the femur 382
  The hip joint during walking and running 383
  Proprioceptive and kinesthetic issues of hip region 384
Hip pathologies 384
  The neuromuscular hip 384
  Developmental dysplasia of the hip (DDH) 384
  Hip joint in cerebral palsy 386
  Hip joint in meningomyelocele 387
  Pelvic obliqueness 388
Hip pathomechanics in specific orthopedic conditions 388
  Hip osteoarthritis 388
  Femoroacetabular impingement (FAI) 389
  Proximal femur fractures 389
  Hip endoprostheses 389
References 390

22. Kinesiology of the knee joint

Gülcan Harput

Introduction 393
Tibiofemoral joint 393
  Normal alignment versus malalignment of the tibiofemoral joint 393
  Tibiofemoral joint motions 394
  Screw-home (locking) mechanism 395
Patellofemoral joint 396
  Patella 396
  Trochlear groove 396
  Normal alignment versus malalignment of the patellofemoral joint 397
  Patellofemoral motion during flexion and extension 398
  Patellofemoral contact area 398
  Patellofemoral joint reaction force 399
  Patellofemoral joint stress in weight bearing versus non-weight bearing 399
Muscular actions 399
  The knee extensors 399
  The knee flexors 401
  Extension strength versus flexion strength 403
Tibiofemoral joint passive static restraints 403
  Knee joint capsule 403
  Meniscus 403
  Collateral ligaments 404
  Cruciate ligaments 404
  Posterolateral corner restraints 406
  Patellofemoral joint restraints 406
References 406

23. Ankle and foot complex 411

Salih Angin and İlkşan Demirbüken

Introduction 411
Bones of the ankle and foot 411
  Tibia 411
  Fibula 411
  Tarsal bones 412
  Metatarsals 415
  Phalanges 416
Joints of the ankle and foot 416
  Proximal tibiofibular joint 416
  Distal tibiofibular joint 416

- The ankle joints 416
- Movement at the ankle joint 418
- Subtalar joint 419
- Movement at the subtalar joint 419
- Midtarsal joint 420
- Movement at the midtarsal joint 421
- Distal intertarsal joints 421
- Tarsometatarsal and intermetatarsal joints 421
- Movement at tarsometatarsal joints 421
- Metatarsophalangeal joints 422
- Movement at metatarsphalangeal joints 424
- Interphalangeal joints 425

Foot arches 425

Muscles of the ankle and foot 427
- Anterior muscles 427
- Posterior muscles 428
- Lateral group muscles 430
- Plantar intrinsic muscles 431
- Dorsal intrinsic muscles 434

References 435

Part 7

Sensory-motor integration and performance

24. Motor control and sensory-motor integration of human movement

Songül Atasavun Uysal and Tülin Düger

Physiological basis of motor control 443
- Understanding motor control 443
- Neuroanatomy and neurophysiology 443

Sensory-motor feedback and perception of movement 443
- Sensory systems 443
- Sensory inputs 444
- Coordination in purposeful movement 445

Motor control and sensory-motor integration in different life stages 446
- Sensory-motor integration 446
- The motor movement 447

The concepts of human motor control 448
- Gravity 448

Linear force 449

Rotatory force 449

Torque 449
- Examples of moving on 449

Disabilities of sensory-motor integration and pathological conditions 450

References 452

Further reading 452

25. Motor learning 453

Şermin Tükel

Introduction 453

Learning hypotheses 453
- Behavioral approach 454
- Cognitive approaches 455
- Physiological approach 457

Stages of motor learning 458

Learning skill in different life stages 459
- Motor learning in expertise 460

Disability of motor learning 461

Motor learning in rehabilitation 461

References 463

26. Balance and postural control 467

Tülay Tarsuslu Şimşek and İbrahim Engin Şimşek

Definition of balance and posture 467
- Balance and Postural control: what is the difference? 467
- Geocentric reference frame 467
- Center of mass, center of gravity and center of pressure 468
- Introduction to integrative models to human postural control 468

Sensory-motor background of balance and postural control 469
- Models of postural control 469

Balance maintaining strategies 469
- CoM and CoP behavior during quite standing - the past and current concepts summary 469
- The clinical relevance 470
- Stabilogram/ posturography 470
- CoP trajectory 470

Balance and posture in pathological conditions 472
- Parkinson's disease 472
- Multiple sclerosis 472
- Stroke 472
- Non-of specific low back pain 472
- Anterior cruciate ligament rupture 473
- Ankle sprain and chronic ankle instability 473

References 474

27. The effects of weightlessness on human body: spatial orientation, sensory-integration and sensory-compensation

Burak Erdeniz and Şermin Tükel

Physical adaptation 477

Musculoskeletal and movement adaptations 478

Spatial orientation 479
Sensory-compensation: sensory integration and sensory weighting 479
Sensory-compensation in weightlessness 480
Sensory compensation and cognitive functions 482
Conclusion 482
References 482
Further reading 486

Part 8
Locomotion

28. Evolution of bipedalism 489

Melek Güneş Yavuzer

Introduction 489
Evolving ideas and theories 489
Evolution of bipedalism 490
  Skull 490
  Arms and legs 490
  Spine 490
  Sacrum 491
  Pelvis 492
  Hip 493
  The knee 494
  Feet and toes 495
Bipedal gait 496
References 496

29. Kinesiology of the human gait 499

Nazif Ekin Akalan and Salih Angin

Introduction 499
Gait 499
Gait terminology 500
  Concentric muscle contraction 500
  Eccentric muscle contraction 500
  Isometric muscle contraction 500
  Kinematics 500
  Kinetics 500
  Ground reaction force (GRF) 500
  Joint moment (*M*) 500
  Moment of inertia 500
  Joint power 501
  Step length 501
  Stride length 501
  Cadence (tempo) 501
  Gait speed 501
  Duration of the stance phase 502
  Duration of the swing phase 502
  Stride duration 502
  Center of pressure (CoP) 502
Gait development 502
Normal gait 503
Methods in gait analysis 505
Ambulation profiles 505
Observational gait analysis (OGA) 506
Kinematic analysis 506
Kinetic analysis 507
Electromyography (EMG) 508
Energy consumption 508
Plantar pressure analysis 509
Physical evaluation and functional scales 510
Gait sub-phases 511
Initial contact 511
Loading response 512
Mid-stance phase 515
Terminal stance phase 516
Pre-swing phase 518
Initial swing phase 520
Mid-swing phase 521
Terminal swing phase 521
References 524

30. Biomechanical principles of the exercise design

Elif Turgut and Gul Baltaci

Introduction 527
Basic principles of exercise 527
Mechanical basis of exercise design 528
  Basic concepts of biomechanics in exercise design 528
  Fundamental concepts of mechanics in exercise design 531
  Internal biomechanics 533
Exercise training 535
  Open kinetic chain exercises 535
  Closed kinetic chain exercises 536
Exercise training across lifespan 536
References 537

Index 539

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Foreword

I am honored to have been invited to write the Foreword of "Comparative Kinesiology of the Human Body" edited by colleagues Prof. Salih Angın and Prof. Engin Şimşek. They have undertaken a big challenge and shown immeasurable patience and persistence in the effort of writing and editing a comprehensive book on kinesiology based on the quest for understanding the underlying issues regarding human anatomy, motion and control. Each of the 30 chapters was written by authors with undeniable experience and the expertise of their contribution is clearly evident. To quote Turkish poet Yunus Emre "bilmez ki sora, sormaz ki bile" "The one who does not know will not ask and the one who does not ask will not know", I hope this book will enable us to ask more questions regarding human movement.

Fatma Uygur
February 4, 2020

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Preface

Kinesiology deals with every moving biological system/structure while establishing the basics of movement interlinked with control and support infrastructures. Indeed, the knowledge attained through kinesiology and related studies may be accounted for as one of the key components to achieve an acceptable level of understanding related to integrated systems approach in health care.

In its core, kinesiology is difficult to master as it depends on and integrates itself with many disciplines to explain what remains in the range that we call "normal". There are several high quality works intercepting the concept of normal. However, the dilemma is that the normal, in a sense, is what we consider as "common" which is not disturbing. For females having slightly wide pelvis (over the approximated anthropometric range) usually goes undetected and even appreciated for a natural delivery, but is it normal? From where kinesiology stands it may help to explain an unusual energy expenditure during gait obviously some kind of pathology during walking. Although defining normal is a crucial point, in this book, the readers are also encouraged to get involved with several pathological conditions or apparently normal conditions that have consequences. It is not possible (and also not logical) to cover all, however, gaining insight about the most common would be a good starting point. Keeping in mind the above-mentioned motivation of referral to pathologies, the essential chapters (you may also call the classics) are covered in detail.

This book has eight parts and 30 chapters. The first part contains four chapters about past-present and future development of kinesiology; basic mechanical principles, fundamentals of human movement, neural control mechanisms and energetics, and architecture of human joints and their movements. Part 2 covers mechanical behavior tissues such as bone, muscles, ligament, tendon and fascia. This is one of the most joyful parts of this book also covering (let's say) not well-known fields that kinesiology has fit itself in, much easier, "morphogenesis and biomechanics of human embryo and fetus". As biomechanical forces are natural parts of the skeletal formation, it must be interesting to know about uterus deflection and reaction force generated by a kick, and force in the muscles surrounding the hip and knee joints in a 20–22 weeks-old fetus.

Parts 3 and 4 cover upper extremity and trunk and pelvis respectively. Part 5 contains two chapters kinesiology of respiration and biomechanics of circulation, which are essential for understanding the underlying mechanisms of cardiovascular and respiratory diseases.

Part 6 covers the lower extremity as it is seen in other classical kinesiology books. Part 7 has distinct features as it covers motor control and sensory-motor integration of human movement, which are other essential topics to understand movement disorders. The motor learning, and balance and postural control, which we rely on during the rehabilitation process are other two chapters of this part.

"Effects of weightlessness on human body" is another chapter of part 7 that has not been covered by existing kinesiology books. While astronauts perform a task in a microgravity environment, they need precise movement, attention, and orientation, which are actually rely on gravity force. It must also be interesting to learn about what happens and how human movement changes if there is no more gravity force acting on otolith organs and semicircular canals, and no more proprioceptive signals raised from golgi tendon organs. Compensatory mechanisms of the brain for missing graviceptor signals may also be interesting to read.

Part 8 has chapters about the locomotion. Probably, the most interesting chapter here in this part is the "evolution of bipedalism", It may be worthwhile to know about why and how we -as humans- are walking on our two feet and how advantageous it is. For readers of this book, studying mechanical and morphological changes on the human body during the evolution of bipedalism could be valuable prior to study gait assessment and analysis. Kinesiology of the human gait is another chapter, which was blended with contributors' clinical experience.

The last chapter "biomechanics of exercise design" contains detailed and concise knowledge that covers mechanical principles of exercise design and fundamentals in the development of an exercise program based on corresponding pathological conditions.

Finally, we have edited a book, which was intellectually challenging work and an instrument in an orchestra must be blended with the whole and was a completely different strike of a brush than those of others painting the same composition, which exposes author's expertise and the scientific level of mastering within their field. As editors, we have put great care and effort into our work, however, we are sure that many mistakes and errors still exist in the book. We hope readers drag our attention to these mistakes and errors so that we can put greater care and effort to improve in future editions.

Salih Angin and I. Engin Şimşek

Acknowledgments

We would like to thank all **contributors** who have been rigorously working for the last couple of years. Also, we present our special thanks of gratitude to the reviewers (although their names are a secret!) whose vision has inspired us all. Without their guidance, this book would never be completed. In addition, we would like to express our sincere gratitude and special thanks to our **companions from Elsevier** Kiruthika Govindaraju-Senior Project Manager, Samuel **Young**-Editorial Project Manager, Ashwathi **Aravindakshan**-Copyrights Coordinator and to those all we could not mention here for their unbelievable patience and supportive manner.

Lastly, to **our families**; we thank for the warm blankets and never empty coffee mugs. We will be forever in debt for your understanding and kindness.

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Part 1

History and basics of kinesiology

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Chapter 1

Past, present and future of kinesiology

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Historical perspective of the kinesiology studies

Human movement has undoubtedly been observed ever since the time of the first human being, however the earliest written comments regarding the manner in which humans walk can be attributed to Aristotle in the fourth century before Christ.

During the Renaissance, Leonardo da Vinci and Galileo Galilei concentrated on the rudiments of biomechanics and Galileo was the first person to marry deductive reasoning with experimental observation.

Rene Descartes first conceived of an orthogonal coordinate system for describing the position of objects in space. In an illustration within his book De Homine published in 1662 after his death, Rene Descartes demonstrated a closed loop motor control with the movement of the arm being controlled by muscular activity under the influence of nerves connected to the brain and with feedback provided by the eyes (Baker, 2007), (Fig. 1.1).

Giovanni Alfonso Borelli, a student of Galileo was among the first scientists to analyze motion and performed the first experiment in gait analysis, and through this experiment he deduced that there was a medio-lateral movement of the head during walking; also developed his theory of muscle action based on mechanical principles. He published "De Motu Animalum" in 1682 and used a scientific approach in his description of walking (Fig. 1.2). For more scientific progress the physical laws governing forces were to be formulated by Isaac Newton in "Mathematical Principles in Natural Philosophy" in 1688 (Whittle, 1996; Banta, 1999; Baker, 2007).

In "Physiologie des Mouvements" published in 1867 Duchenne; the founder of electrophysiology; described the function of individual muscles of the human body. It is accepted to be the first scientific systematic evaluation of muscle function (Banta, 1999).

Development of kinesiology in modern age

During the early nineteenth century, the first formal biomechanical investigations were made by the Weber brothers in Germany (Whittle, 1996; Banta, 1999; Andriacchi and Alexander, 2000). In 1836 the Weber brothers, Edward and Wilhelm published their book "Mechanics of the Human Walking Apparatus" in which they gave the first clear description of the gait cycle. They conducted experiments utilizing a stop watch, measuring tape and a telescope and made accurate measurements of the timing of gait and of the pendulum-like swinging of the leg of a cadaver. They were the first to develop illustrations showing the attitude of the limb segments at different instances of the walking cycle (Baker, 2007), (Fig. 1.3).

The earliest kinematic studies on human walking were performed in the 1870s by Marey in France and Muybridge in the States. These early investigations were made using still cameras; Marey utilized chronophotograph whereby a single plate camera had the shutter opened and closed at fixed time intervals, thus recording on the plate successive positions of the human body during function; he made multiple photographic exposures, on a single plate, of a subject who dressed in black, except for brightly illuminated stripes on the limbs. He also investigated the path of the center of gravity of the body and the pressure beneath the foot (Fig. 1.4). Maybridge used a series of cameras to take multiple pictures in rapid succession of both animals and humans in movement (Whittle, 1996; Paul, 1998; Andriacchi and Alexander, 2000).

Also, during that time period Wilhelm Braune and Otto Fisher reported measurements of body segment movements to calculate joint forces and energy expenditures using Newtonian mechanics. They photographed the subject with four cameras. One camera was positioned in front of the subject, one behind and one on each side,

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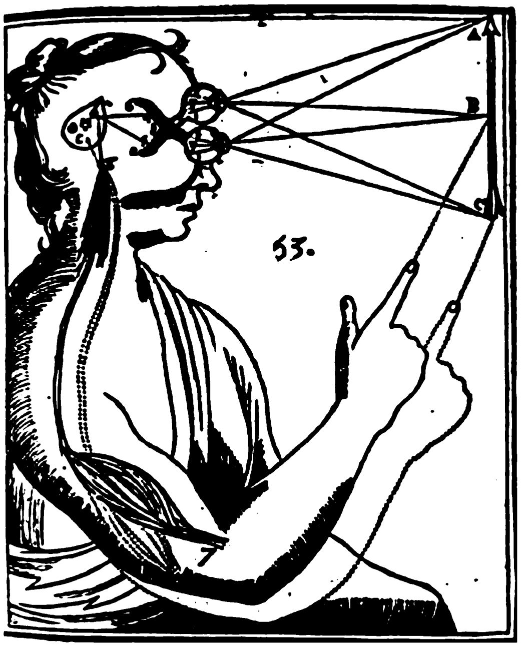

FIGURE 1.1 Somatosensorial and visual senses in controlling voluntary movement.

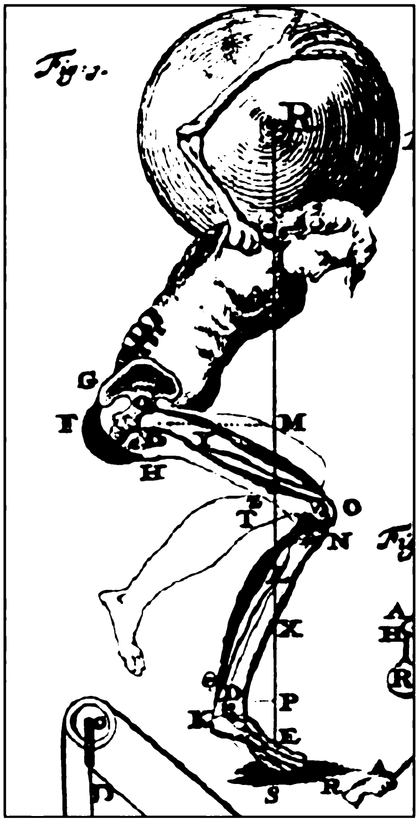

FIGURE 1.2 Illustration of walking, the first scientific approach to gait analysis based on mechanical principles.

making the measurements three dimensional. The process of collecting data alone required 8–10 hours per subject and months to calculate kinematic measurements (Paul, 1998; Banta, 1999; Andriacchi and Alexander, 2000; Sutherland, 2002; Baker, 2007). Wilhelm Braune and Otto Fisher published their work in 1895 "Der Gang des Menchen" which is considered to be the first 3-D gait analysis (Baker, 2007).

Marey's students Carey, Ampar and Demeny searched for scientific methods of recording the magnitude of foot-heel contact. Demeny developed a pneumatic mechanism which measured the vertical component of the ground reaction (Sutherland, 2005; Baker, 2007).

Jules Amar was the first to develop a three-component pneumatic force plate. Amar was a rehabilitation doctor working with amputees after the First World War (Fig. 1.5). Elftman later developed a full-three component mechanical force plate in 1938 and commercial strain gauge platforms became available in the 1970s (Sutherland, 2005; Baker, 2007).

A full understanding of normal gait requires the knowledge of which muscles are active during different parts of the gait cycle. The Berkeley Group headed by Inman and Eberhart at the University of California was assembled as a result of the causalities of the Second World War to advance prosthetic devices for war veterans. This group made the biggest advances in gait analyses. Vern Inman and colleagues moved the science of gait analysis dramatically forward by adding kinesiological electromyography, 3-D force and energy measurements in the study of walking in normal subjects and amputees (Sutherland, 2001).

In his landmark article "clinical gait analysis a review" published in Human Movement Science in 1996 Whittle states that "clinical gait analysis" consists of five elements: videotape examination, measurement of general gait parameters; also known as temporo-spatial parameters of gait; namely cadence, foot angle and with stride lengths and speed; kinematic measurements made by television cameras linked into a computer, which define the movements of the major joints of the lower limb in 3 dimensions; the objective measurement of ground reaction forces using the force plate (platform) beneath each foot while walking and EMG from specific muscles. By combining kinematic and kinetic data it is possible to calculate the joint moments and powers in 3 dimensions (Whittle, 1996).

According to Whittle, interpretation of the mechanics of gait is best conducted using the angle, moment, power-calculated by means of inverse dynamics and EMG charts.

As pioneered by Braune and Fisher, Eberhardt and Inman also recognized the importance of measuring the displacement of whole body and individual joint

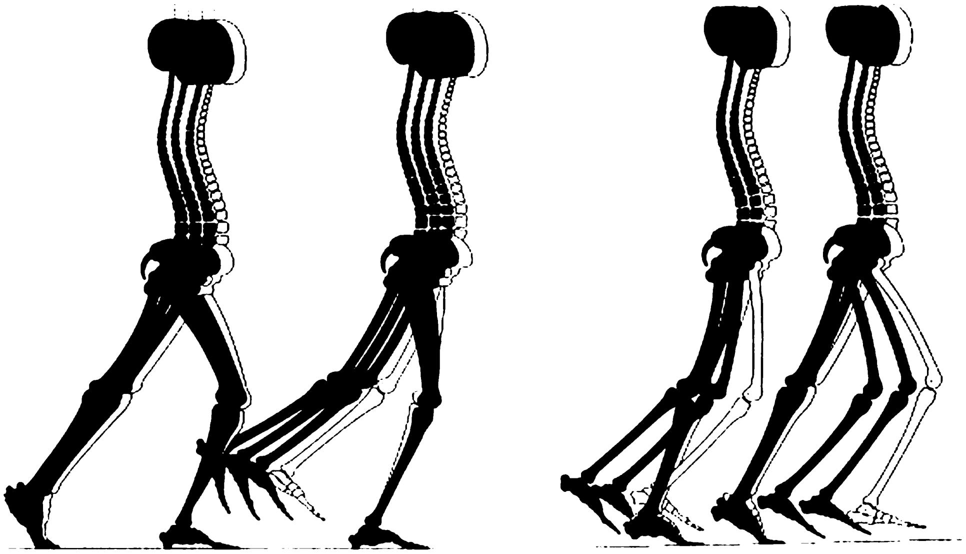

FIGURE 1.3 First description of a gait cycle and instant position of limb segments in pendular motion.

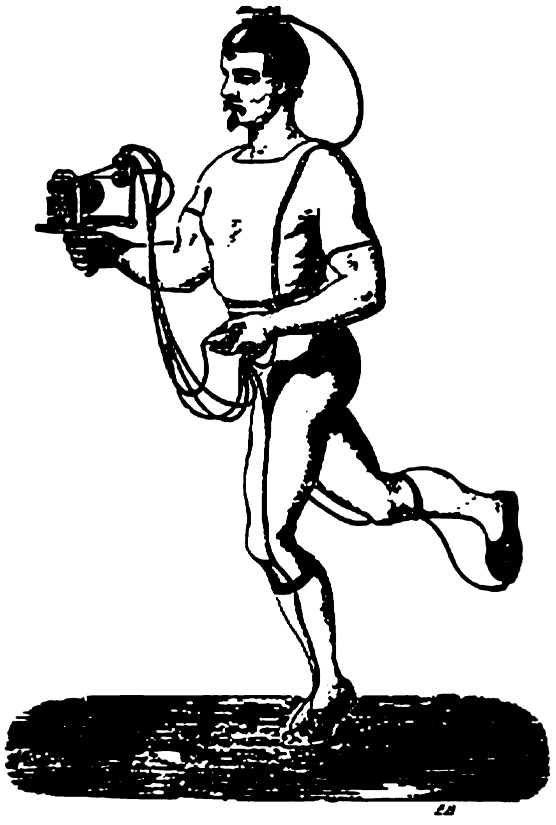

FIGURE 1.4 Investigating the path of center of the gravity and movement of the limb segments of a person with fixed illuminated stribe on on his limbs and head.

segments. However, their method for measuring kinematics of normal gait was by using bone pins on volunteers, an invasive and painful method. The work of the Berkley group is contained in Saunders, Inman and Eberhart's landmark article and in the seminal test "Human Walking" (Inman et al., 1981).

Murray, a physical therapist devised a noninvasive and effective method to measure moments. She attached reflective targets to specific anatomic regions with subjects walking in the illumination of a strobe light and the photograph was used to make measurements of segments. Her measurements were quite accurate, but they were also time consuming since there was a need for manual measurements of all joint angles. (Sutherland, 2002; Baker, 2007) However, she and her coworkers produced some classic articles (Murray et al., 1964, 1970, 1985a,b).

Sutherland is yet another pioneer in the clinical application of gait analysis techniques; he began making use of data to provide treatment recommendations and study the outcome of interventions (Sutherland, 1978; Sutherland and Cooper, 1978; Sutherland et al., 1981). In the late 80s and 90s Gage, De Luca, Ounpuu and Davis made various contributions on the treatment, surgery and outcome of surgery especially in children with cerebral palsy (Gage et al., 1984, 1987; Gage, 1990, 1993, 1994; Ounpuu et al., 1993a,b; DeLuca et al., 1997, 1998; Sutherland, 2002).

Kinesiological EMG is defined as a technique to determine the relationship of the muscle activation signal to joint movement and to the gait cycle (Sutherland, 2001). Jacquein Perry can be considered to be the pioneer of kinesiological EMG. Using surface electrodes, educating and conducting a group of physical therapists in her gait laboratory. Perry carried out many investigations; the summary of her years long research was published in 1992 in her landmark book, "Gait Analysis: Normal and Pathological Function" (Perry and Davids, 2010). Jacquein Perry and David Sutherland; both students of

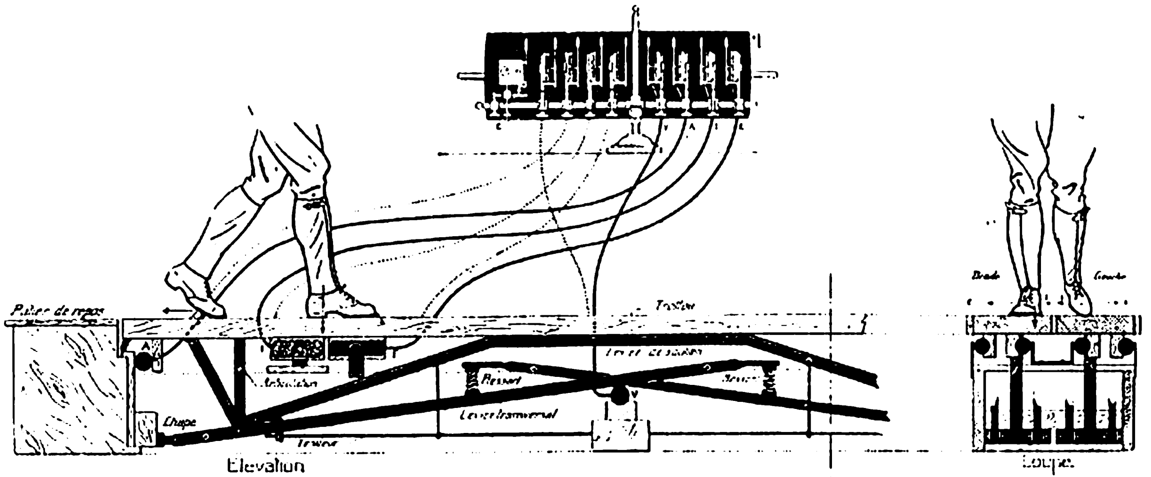

FIGURE 1.5 Amar's pneumatic force plate.

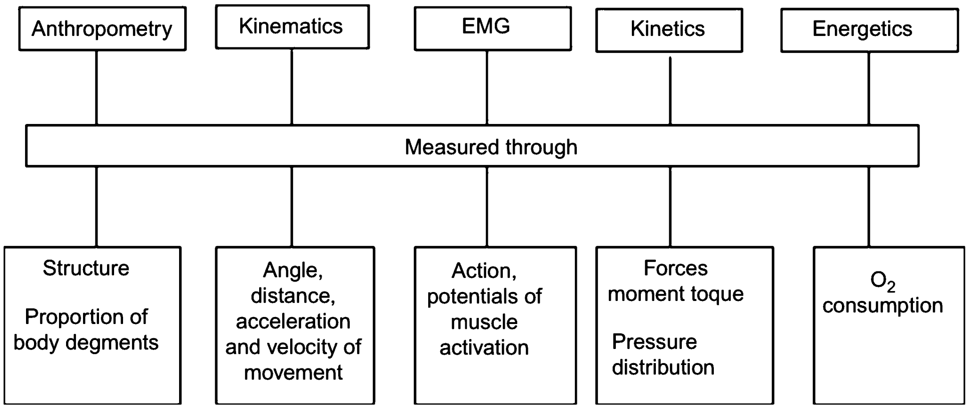

FIGURE 1.6 Five major areas of kinesiological measurements and analysis.

Inman; made various contributions to the clinical application of gait analysis to assist in the treatment of patients with locomotion disorders, especially with cerebral palsy (Sutherland et al., 1969; Perry and Hoffer, 1977; Sutherland, 1978, 1984; Gage et al., 1987; Perry, 1987).

After Amar and Elftman with the understanding that kinetics is another vital component of gait analysis, many scientists contributed to improve the force plate (force platform) design and used it for the identification of anomalies of locomotion. Winter deserves the main credit for the routine clinical use of moments and powers (Winter, 1979, 1981, 1986; Winter and Eng, 1995; Sutherland, 2005). We once again come across Ounpuu, De Luca and Davis analyzing gait in children with special reference to kinetics (Ounpuu et al., 1991, 1996; Rose et al., 1993).

The metabolic energy costs of gait and other activities is another clinical aspect of kinesiology. Ralston inferred that the rate of energy consumption could be calculated by analyzing the composition of the gas respired from the lungs of the subjects. He developed equipment in which respired air was collected in large bags, known as Douglas bags (Ralston, 1958; Paul, 1998). Modern technology has brought small size electronic flow and analysis equipment, which can be worn by the test subject even in stressful athletic performance and these transmit data by radio telemetry to monitoring equipment. (Paul, 1998) Still another example of the development regarding oxygen consumption measuring equipment is the Cosmed System, which is entirely portable and self-contained on the subject (Corry et al., 1996; Sutherland, 2005). Jessica Rose, a physical therapist, utilizes heart rate measurements in her research related to energetics of gait (Rose et al., 1989, 1991, 1994). The energy expenditure of gait is especially important when determining the most appropriate orthotic device in patients with walking disabilities (Thomas et al., 2001; White et al., 2002).

Kinesiological measurements and analysis can basically be separated to five major areas, anthropometry, kinematics, kinesiological electromyography, kinetics, energetics (Fig. 1.6).

Although since the 1960s there have been serious attempts to take gait analysis out of the research laboratory and into the clinic, the amount of time required to process data and to interpret this data for the clinical management of patients were main obstacles, preventing its widespread usage. It was not the routine in clinics until the 1980s. Since then there has been a steady increase in the use of gait analysis in the clinical management of the patients. We now have gait clinics in many hospitals especially university hospitals all around the world.

A 3-dimensional gait laboratory usually has a computer system with 8 infrared cameras, 2 force platforms, 12 channel telemetric EMG, a pedobarograph and a system for measuring energy consumption. The patient dresses so that the lower limbs are exposed for reflective markers to be placed on the skin. There is a continuous development in software and with increasing computer memory, markerless measurements of 3-dimensional motions may widely be in use in the near future (Sutherland, 2002). However, there is still a debate on how this data should be best used, the need for a concise index is obvious; a gait summary measure that indicates the degree of gait deviation from normal and stratifies the severity of pathology. Normally index (NI), hip flexor index (HFI), gait deviation index (GDI), gait profile score (GPS) and GDI- Kinetic have been proposed. In a review paper aiming to provide an overview of the most frequent gait summary measures that have a clinical application, it is stated that efforts should be made to develop a new summary measure that can be deconstructed into single gait variable and at the same time include spatio-temporal parameters, EMG and kinetic data (Cimolin and Galli, 2014).

Although studies of kinesiology were historically, mainly studies about human locomotion consequently gait analysis, we know that human motion is not merely gait; movement science also encompasses upper extremity and the torso.

There are vast developments in medical imaging and combining dynamic visualitions obtained from MR scans with kinetic and kinematic data obtained in a motion laboratory will enhance our ability of understanding human motion, thus improving clinical outcomes (Andriacchi and Alexander, 2000). As the science of motion analysis advances, new and more powerful observation and modeling techniques and stimulation studies will develop allowing the evaluation of functional outcomes of surgery and gaining insight for therapy planning (Akalan et al., 2016; Saglam et al., 2016; Siasios et al., 2017). predicting occupational injury risks in sports medicine, understanding muscle fatigue and monitoring changes as a result of disuse, training and aging (Akalan et al., 2008, 2015; Benbir et al., 2010; Harput et al., 2013, 2014, 2016; Christian and Nussbaum, 2015); even the effects of everyday social life such as back loading of school books in children (Merletti et al., 2001; Seven et al., 2008, Ozgul et al., 2012).

Advances in movement science and computer software, has made it possible to carry out simulation-based studies. These simulation models have enabled the identification and treatment of gait problems and movement disorders. They have also enabled scientists to measure variables such as stability, robustness and coordination (Casey Kerrigan et al., 1998; Luengas et al., 2015). However, to comprehend the present and how this led to the era of robotics, we must go back nearly a hundred years to the contribution of the "fathers of motor control"; the neurophysiologists Charles Sherrington, Nikolai Bernstein and the theory of dynamic systems (Latash, 2008). Sherrington introduced the idea of reciprocal inhibition, described the tonic stretch reflex and developed a theory of movements based on coordinated changes in muscle reflexes; while Bernstein introduced the elimination of redundant degrees of freedom, and the hierarchical control of movements. Along with Graham Brown, Bernstein claimed that natural voluntary movements could be generated within the central nervous system, leading to the idea of central pattern generators and the physiology of activity (Bernstein, 1967; Latash, 2008).

With the advances in motor control and motor learning and the use of system dynamics models it has been possible to create humanoid robots with artificial intelligence (McGeer, 1990; Adamovich et al., 1994; Steels, 1994; Brooks et al., 1995; Schaal, 1999; Ritter et al., 2003; Schack, 2003; Rosenbaum et al., 2007, 2011). Although feared by some futurists and those afraid of losing their jobs, robots smarter than human beings have become inevitable in today's society. Who can deny the fact that a robot checking a nuclear energy reactor, much more efficiently than a technician or an engineer is a vast advance for humanity?

Through movement science we came to understand the importance of core stabilization; and that the movements of the upper and lower extremities begin with the contraction of the trunk muscles. We realized that treating the extremities would be more effective by incorporating core stabilization exercises as well (Ayhan et al., 2014).

As a result of human motion analysis, we have gained insight into the mechanisms of motor learning, feed forward and feedback control, feed forward insufficiencies, anticipatory planning deficits, how feedback delays and error monitoring processes differ in healthy individuals and those with neurological disorders. We have learned means of optimizing feedback effects on skill acquisition (Mutsaarts et al., 2006; Sullivan et al., 2008; Wagner and Smith, 2008).

In 1995 by analyzing the gait of healthy individuals Hausdorff and colleagues showed the presence of long-range self-similar correlations extending over hundreds of steps; the stride interval at any time depended on the stride interval at remote previous times (Hausdorff et al., 1995). Following this milestone, others carried out work regarding the nature of the gait dynamics and gait patterns (Hausdorff et al., 1995; Hausdorff, 2005; Bollens et al., 2014).

What is the implication of gait patterns? Human gait can be used as a biometric feature for personal identification of smart surveillance systems for security sensitive areas. The combination of human motion analysis and biometric identification is important for some security sensitive applications. The aim of smart surveillance is detection, tracking and behavior understanding. In other words, human motion analysis may enable security personal to detect a terrorist, to track his or her movements and most importantly understand whether he or she is planning a terrorist attack (Wang et al., 2003).

Without the advances in human motion analysis it would not be possible to design or produce the endoprosthesis, limb prostheses, orthoses or other rehabilitation devices that we currently use (Horak et al., 2015; Tucker et al., 2015; Atzori et al., 2016; Rasmussen et al., 2018).

Before contemplating about the future, we should acknowledge that kinesiology has yet another past, another history intermingled with social, even political events. It would be unfair to skip it and claim that the history of kinesiology is related purely to scientific developments.

The first record of the word "Kinesiology" appears in the biography of Peter Henry Ling; the founder of the Royal Central Institute of Gymnastics (RCIG). Kinesiology originated from two Greek words; kinesis meaning movement and logos meaning study. The biography of Ling, who can be considered to be the father of Swedish gymnastics, was written in 1854 by Carl August Georgie, a Swedish physiotherapist practicing in London, also a former teacher of the RCIG in Stockholm (Ottosson, 2010).

Swedish gymnastics was probably one of Sweden's most successful cultural exports of the nineteenth century and like contemporary art and literature it took its roots from national romanticism. The Swedish army, like many other countries in Europe had suffered humiliating defeats. The Swedish believed that the lack of success in the battlefield was due to the fact that the whole nation had degenerated. Consequently, gymnastics and physical exercises were considered to be necessary to restore the nation's defense capacity. Ling founded the RCIG in 1813 as a state-owned institution responsible of training skillful physical educators. Ling believed that gymnastics had to be something more than just strengthening exercises; consequently, there were classes in anatomy, pathology, physiology and movement science. So the graduates of RCIG were not merely physical educators for youngsters, they were also physiotherapists and military gymnasts. Along with Georgii; the author of Ling's biography; there were others doing missionary work all over Europe and even across the Atlantic in the name of Ling's gymnastics. Many physicians, military personnel and interested people from all over Europe visited the RCIG. One of the graduates was Ali Sami Yen who was one of the most prominent sports figures of Turkey in the early 20th century. Lieutenant Baron Nils Posse introduced the concept in Boston during 1890s (Ottosson, 2010; Sporis et al., 2013).

The majority of physical education departments in the USA and Europe were established soon after the Second World War with the aim of preparing physical education teachers; however physical education programs focused on occupational preparation and therefore lacked scientific substance. The desire of being recognized and appreciated by the scientific community would lead to changes. The changes also came about due to social and political events. In 1957, during the cold war years, the Russians launched "Sputnik", the world's first satellite. This event had a shocking effect in the west, especially the United States. Catching up to the Soviets was considered a matter of national security and prestige; and in reaction a Scientific Advisory Committee was established with the aim of increasing time and money spent on science and mathematics and increasing scientific output of colleges and universities. In this atmosphere Bryant Conant and Franklin Henry endeavored to shift physical education toward academic and scientific respectability in the early 1960s (Ottosson, 2010; Twietmeyer, 2012; Sporis et al., 2013).

At the same period universities were also exploring curriculum reforms. Department structures that were teaching oriented, were being abolished. The University of California Physical Education Department adopted the title "Department of Kinesiology" in 1975, and many were to follow (Sage, 2013). We also see this trend of gaining academic and scientific respectability in the establishment of scientific organizations and journals. In the mid 80s the American and European Societies of Gait and Clinical Movement Analyses were established. The International Society of Posturography was founded in 1969. It was renamed as the International Society of Posture and Gait Research in 1986 and its official journal "Gait and Posture" was first published in 1992 (Knudson, 2016). The International Society of Electrophysiological Kinesiology was founded and started publication of the Journal of Electromyography and Kinesiology in 1991 (Herzog, 2002). The American Academy of Physical Education changed its name to the American Academy of Kinesiology and Physical Education (AAKPE) in 1993 and to the American Kinesiology Association in 2007, with the aim of promoting and enhancing kinesiology as a unified field of study (Sporis et al., 2013). It's official journal "Kinesiology Review" is published quarterly. The International Society of Motor Control was established in 2002; its official journal is Motor Control.

Whether the teaching, training educational model for academic physical activity should be abolished altogether is an ongoing debate. In 1990 Karl Newell published three articles in Quest which led to the widespread use of the name kinesiology and had a profound impact on the direction of the field. He claimed that the core of the discipline should be physical activity, not physical education (Newell, 1990a,b) and reiterated his ideas in a 2007 article (Newell, 2007).

On the other hand, Anderson reminds kinesiologists of the power of sport experiences to wake one to their own humanity and points out that the gym class is anything but a triviality for kinesiology (Anderson, 2001, 2002). Twietmeyer claims that kinesiology is neither a pure science nor solely a member of humanities, but rather a field that encompasses both, and insists that to move kinesiology forward the careful acquisition of scientific knowledge is required (Sporis et al., 2013; Twietmeyer, 2018). Rose states that the failure to integrate theory and practice within the curriculum and address real world problems is the major challenge to the successful aging of kinesiology in the 21st century (Rose, 2008). Culp takes part in this debate claiming that to adjust to the changing times the curriculum should focus on the concept of social justice (Culp, 2016). Mark Latash argues that to better understand and study motor control-which is considered to be the youngest and most rigorously developed sub discipline in kinesiology one has to have a solid background in the theory of nonlinear differential equations, physics and neurophysiology. He claims that the main challenge of kinesiology is turning it into an exact science like physics while Knudson states that kinesiology must emphasize the applied nature of the field and its impact on public health (Latash, 2008; Knudson, 2016).

Kinesiology in 21st century and beyond

When we look at the programs of international conferences and articles written on this issue we realize that this debate stemming from the social history of kinesiology; will continue into the future.

In this era of the fourth industrial revolution with artificial intelligence, machine learning, visual reality, augmented reality, big data, robotics, autonomous vehicles, 3D printing, quantum computing, individualized medicine, ultra-high-speed imaging and nano technology it's hard to predict the future of kinesiology. However, the connection between cognitive function, healthy aging, hypo-kinetic diseases and preventive physical activity has become more and more apparent. Kinesiology is well positioned in that promoting physical activity will be the most cost-effective intervention of addressing these public health issues in the future (Hillman et al., 2008, 2011; Rose, 2008; Knudson, 2016).

Another field in which movement science will have an impact on is the advancement of robotics. Robot learning has enabled robots to behave socially, walk, navigate, identify opponents and score goals in robot soccer. By translating findings in studies of motor control in humans into simulation models, it has been possible to replicate complex movement abilities in robots (Mataric, 1998; Schack and Ritter, 2009).

Robotic sports are still in its infancy, but the Federation of International Robot-Sport Association (FIRA) began organizing an annual world championship in soccer in 1997. In 2018 the winter olympics took place in South Korea and 8 robotic teams competed for their own gold medals in robotic skiing; however, they tumbled over relatively flat slopes. FIRA has set its goal of having a robotic team beat the human world champions in 2050. So, watching Robotic Olympics in an Olympic stadium or on TV may well be in the future. The role of kinesiology in the realization of this idea is obvious.

Another area in which movement science has made and will be making contributions is human biomechanical responses to partial gravity. Research on the effects of microgravity began before Apollo Astronauts set foot on the moon in 1969. As the exploration of the moon or Mars is envisaged, present research seeks to find the best medical and exercise support to maintain astronauts' health during future missions in partial gravity (Shavelson, 1968; Berry, 1974; He et al., 1991; Davis and Cavanagh, 1993; Kram et al., 1997; Richter et al., 2017).

The most recent developments in human motion analysis have led to the detection, tracking and recognition of human activities through image sequences (Wang et al., 2003). Human gait has been used as a biometric feature for personal identification (Little and Boyd, 2001). In their 1999 review of human motion analysis Aggarwal and Coi stated that recognition of human motion is in its infancy (Aggarwal and Cai, 1999). Technological progress and events- especially terrorist attacks of the last 20 years have led to giant steps being taken in monitoring human activities. Not only national security authorities but also companies such as IBM and Microsoft are investing on research on human motion analysis (Wang et al., 2003).

Activity recognition has led to pattern recognition and this has led to detecting intent, in other words intent recognition (Wang et al., 2003; Aggarwal and Ryoo, 2011). Surveillance systems in public areas such as airports, subway stations, power plants, oil refineries and even schools aim to understand what is going on in the mentioned area, in other words to detect criminal intent (Aggarwal and Ryoo, 2011; Porikli et al., 2013).

The importance of these advances in preventing crime is unquestionable; however, detecting intent can also be skating on thin ice. In the hands of a dictator this will mean detecting people who intend to organize a peaceful protest for human rights or social justice. Advances in movement science also hold the silver bullet for the creation of "big brother" of George Orwell's famous dystopia "1984".

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Chapter 2

Principles of kinesiology

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Basic information

Introduction to kinesiology

As the robots started to participate in our lives more than ever nowadays, a big difference in our movement characteristics, the aesthetic of the human movement, still exists. The aesthetic of human movement is subjected in many masterpieces as well, such as Michelangelo created in sculpture and Leonardo Da Vinci performed in painting. The complexity of the human movement and interaction between muscles are responsible for performing movements in an aesthetic way. It is indeed a necessity to understand how human body moves so perfectly, thus the Kinesiology Science has been born. A kinesiology term comes from Greek words of 'kinesis' (movement) and 'ology' (the scientific study of a particular subject) and means 'studying the movement'. Kinesiology needs three key elements to be understood correctly, Anatomy, Physiology, and Biomechanics.

Anatomy is the art of knowledge related to shapes, structures, locations, and neighborhoods of human body parts. In terms of kinesiology, anatomy helps to anticipate which body parts or structures will play a role in a specific movement.

Physiology aims to understand how the living organism and each sub-systems, organs or cells of the human body are working.

Biomechanics is an effort to get an insight how internal and external forces act on human body structures by using physic rules. Biomechanics uses the applications of mechanics such as statics, dynamic, solid and fluid mechanics, and adapts them into human body. In terms of biomechanics, statics, as the name suggests, interests about static situations such as how bones are loading in different human positions. In contrast, dynamics is related to movement description such as gait analysis. While, solid mechanics are used for creating equations for biologic systems and evaluates the functional behavior under different loading conditions, fluid mechanics helps to understand how blood in the veins or air in the lungs travels.

Kinematics and Kinetics are further subdivisions of biomechanics. Kinematics might be thought as the cinematic of a movement, as the resemblance between the words. Kinematics interests the appearance of a body motion. Timing and sequencing are some characteristics of the movement which kinematics is involved. On the other hand, kinetics investigates the forces such as pulling or pushing during movements (Hall, 2011; Nordin and Frankel, 2012; Neumann, 2013).

Having knowledge of kinesiology might serve well to rehabilitation professionals in many ways. By using kinesiology, the rehabilitation professional can predict future injuries, can establish most suitable exercises both for rehabilitation and performance enhancing, and can implement external supports when needed. This chapter aims to define basic concepts and fundamental physics laws for providing a scientific background to the readers.

Cardinal plane and axes of motion

Axes and planes are used to describe body movements. Since body parts can be in various positions during body movements, axes and planes are defined according to the common anatomical position in the world. There are three main planes and three movement axes. Planes divide our body into three sections of sagittal coronal and transverse. In addition, frontal, sagittal and vertical axes are included (Fig. 2.1).

The transverse plane divides our body into superior and inferior segments. The vertical axis is perpendicular to this plane. Internal and external rotation movements occur with this plane and vertical axis. The other half of these movements is horizontal flexion and extension movements. The vertical axis moves from top to bottom or from cranial to caudal (Fig. 2.2).

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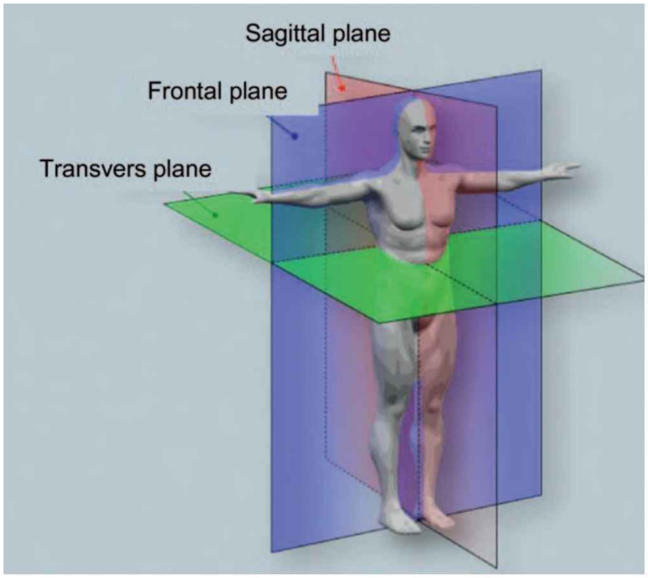

FIGURE 2.1 Cardinal planes and axes.

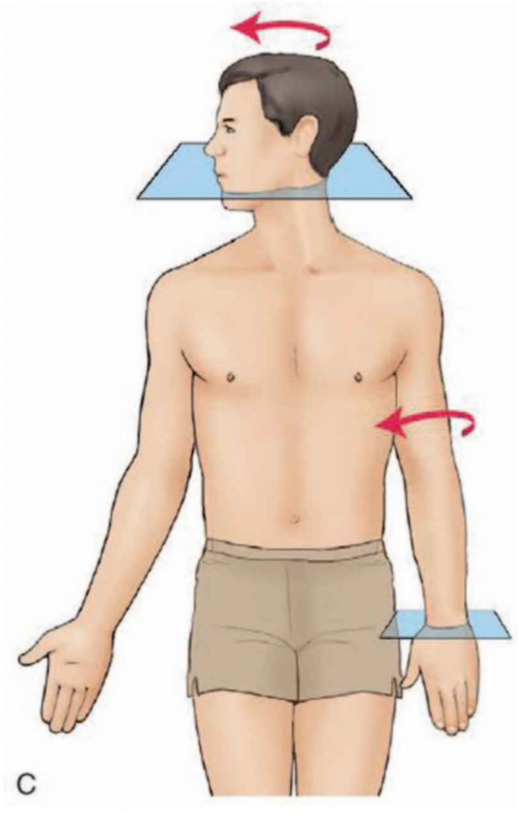

FIGURE 2.2 Internal and external rotation motions.

The coronal plane separates the body anteriorly and posteriorly. The axis of this plane is the sagittal axis. The sagittal axis is located in the direction from the front to the back of the body. The coronal plane is also described in the literature as a frontal plane. abduction and adduction movements occur in this plane and axis. As an example of the shoulder joint, abduction movement occurs in accordance with the sagittal axis from the anteroposterior direction (Fig. 2.3).

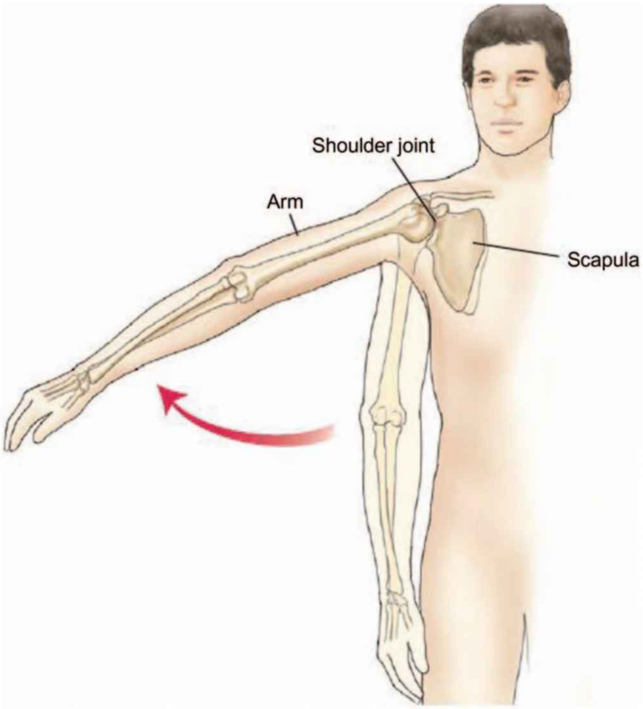

FIGURE 2.3 Abduction and adduction motions.

The sagittal plane divides the body into right and left. The axis of this plane is frontal axis. In accordance with this plane and axis, flexion and extension movements occur. As can be seen from the figure, the knee joint movement, the axis is moving from left to right and knee joint flexion movement occurs. There is also a special description for this plane. The plane that divides the body into two equal parts is called midsagittal plane. It is also called the symmetry line (Fig. 2.4).

The movements that occur in accordance with the plane and axes are described above. In cases where shoulder joint movements are attempted to be identified, the above planes and axis are valid but in some joints movements do not occur on a single plane and axis. An example of this is ankle movements. Ankle joints can create complex combined movements in daily life in order to adapt the ankle to the floor. Subtalar joint movements, in particular, do not correspond to the aforementioned movement skates. The eversion movement is observed with plantar flexion and adduction movements. Inversion movement is observed with dorsiflexion, abduction movements. These movements are defined as triplanar movements. In addition to this, vertebral joint movements do not correspond to the aforementioned planes and axes (Hoffman, 2009; Hamill et al., 2015).

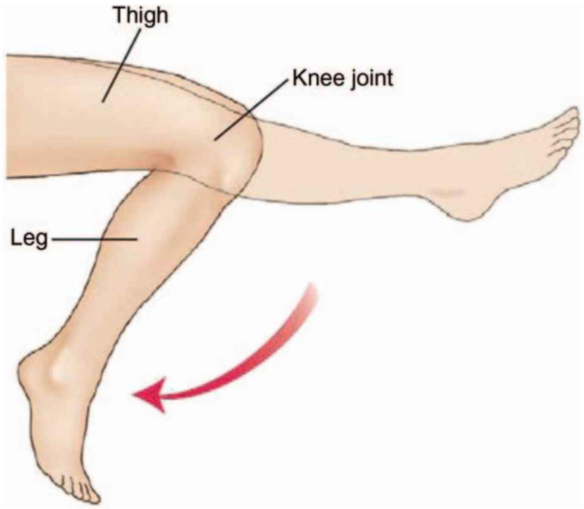

FIGURE 2.4 Flexion and extension motions.

Motion

The motion is defined as changes of position in place. Kinetic and kinematic definitions are used to define motion.

Kinematic parameters describe time-dependent geometric changes associated with movement, independent of the forces that generate motion. In the definition of human movements, the kinematics science examines the change of body posture over time as joints, bones, segments. Deviations in movement can be found in the segment or in a segment away from the segment related to the examination of the body as a whole. When examining the kinematic data, it may be thought that the movement of the related segment may be increased or decreased, or there might be early or late joint movement angles in a defined movement pattern. It is not interested in the amount of force required for these movements or the amount of force that occurs during these movements.

Kinetic parameters are related to the forces that generate motion. During walking analysis, the knee joint is interested in kinematics with the extension angle, while the quadriceps femoris muscle torque, the forces on the joint and kinetic science are involved. A joint with impaired strength or a function of the muscles forming the function will not be able to produce sufficient response to the elimination of related joint reaction forces. Kinetic science examines the effects of internal and external forces on each other.

Diagnosis of movement disorders related to examination and evaluation of the movement can be made. It is important to know the normal functioning and mechanism of human movement in order to diagnose the movement disorders. This mechanism and mechanism is possible by knowing the normal body kinetic and kinematic parameters. With the correct diagnosis, the patient's problems can be examined in a good way and appropriate treatment can be offered. The analysis of the movement to be carried out here can be done observationally or it can be done with the systems that allow further analysis. The analysis of the movement can also be performed in accordance with the sports branch in which the relevant movement pattern is required or by evaluating the desired movement. For example, the elbow flexion movement, which is desired to gain, is evaluated by the problems that limit the capacity and capacity of the function in the joint by performing different conditions (with / without weight in hand).

Motion is simply divided into two groups;

- Linear motion
- Angular motion

Translational or linear motion is the name given to all of the body parts in the same direction, reaching the same distance in the same time. With the movement of a glass in a single plane, all the components of the cup move in the same speed and direction and this movement is called translational motion. The body can move in different directions in different time periods, but makes translational movements in separated time periods.

Rotational or angular (angular) movement occurs when the body follows a circular motion pattern. Where the movement is around an axis of rotation, the body or body parts moving in the same direction in the same time interval. When opening the bottle cap, the movements of the corresponding fingers relative to the center of the lid may be given as an example.

Translational and rotational movements in the general movement pattern emerge as a combination and simultaneously. General body movement patterns appear to be appropriate for this movement pattern. Analysis of the movement pattern is more difficult than rotational and translational movements. In kinematic analysis, translational movements are used with linear kinematics and rotational movements are used as angular kinematics. When defined in this way, the forces required for the emergence of angular movements are called torque. In linear movements, the whole force is called net force. These movements, which are compounded in general movement patterns, are not evaluated independently in the analysis of body movements. Angular and linear movements are calculated as parts of a whole.

Spatial and temporal parameters of gait can be examined through the kinematic analysis. Kinematic analysis covers speed, distance and position of the moving object or human being.

Due to gravity and movement, forces have a permanence effect on the body and lead to continuous "ebb and flow" activity between imbalance and balance. Motion and forces are closely related to each other and motion always causes changes of body configuration (Rau et al., 2000; Axhausen, 2007; Hamill et al., 2015).

Mathematical fundamentals

To apply the principles of kinesiology to the human body, basic knowledge of mathematical fundamental is necessary. This section is a short, basic introduction to mathematical concepts and terminology used in biomechanics.

Units of measure

It is difficult to estimate the magnitude of the any quantity, if measurement is not used. If a quantitative analysis is conducted for collecting kinematic or kinetic data, it is obligatory to present the findings in the correct units of measurement. The magnitudes of measurements are typically given in a specific unit. There are two main systems for specifying units of measure, the Imperial System of Measurement (English System) and the International System of Measurement (the Système International d'Unités-SI, Metric System). Some units of measurement used in biomechanics are given in Table 2.1. In scientific research literature, the metric system is used exclusively in the study of biomechanics (Oatis, 2004; Loudon et al., 2013; Hamill et al., 2015).

Scalars and vectors

As mentioned above, the measurement of physical quantities such as force, time, mass, length, angular speed, displacement is the integral part of biomechanics. A physical quantity can be classified into two categories: 1. Scalar quantities and 2. Vector quantities.

Scalar quantities

Scalar quantities are described completely by their magnitude or their amount. For example, mass, volume, distance, speed, temperature, power, etc. are all scalar quantities. These types of quantities have magnitude only and no direction.

Vector quantities

Some physical quantities, on the other hand, cannot be described fully by their magnitude. For example, when one runs, distance and the direction are important to describe the displacement exactly. Therefore, a physical quantity that is described fully by its magnitude and also its direction is called a vector quantity. Force and torque are kinetic vector quantities; displacement, velocity, and acceleration are kinematic vector quantities (Oatis, 2004; Loudon et al., 2013; Hamill et al., 2015).

Vector analysis

The way of representing vector is using directed line segment with an arrow at one end. The length of the arrow gives information regarding the magnitude of the vector. The direction of the arrowhead in which the arrow points is the direction of the vector. In addition, a complete description of a vector also includes its orientation and point of application (Fig. 2.5).

Vector analysis is a branch of mathematics that involves the composition and resolution of vectors. Vectors and vector analysis are commonly used in biomechanics to calculate forces (such as muscle, resistance and joint reaction forces) and moments.

It is known that vectors are used to represent forces. If you want to define vector components along X- and Y-axis, you will need the resolve the vector. In other words, the process of splitting a vector into various components is called resolution of vectors.

When vectors are added together, this is known as vector composition. In musculoskeletal biomechanics, there may be more than one force acting simultaneously

TABLE 2.1 Base units used for biomechanical measurements.

Base quantity	English (symbol)	Metric (symbol)	Conversion of units
Mass	slug	kilogram (kg)	1 slug = 14.59 kg
Length	foot (ft)	meter (m)	1 ft = 0.3048 m
Time	second (s)	second (s)	1 s = 1 s
Force	pound (lb)	Newton (N)	1 lb = 4.448 N
Pressure	pounds per square inch (psi)	pascal (Pa)	1 psi = 6895 Pa
Energy	foot pounds (ft-lb)	joule (J)	1 ft-lb = 1.356 J
Power	horsepower (hp)	watt (W)	1 hp = 7457 W
Temperature	Fahrenheit (°F)	Celsius (°C)	°F = (°C x 9/5) + 32°

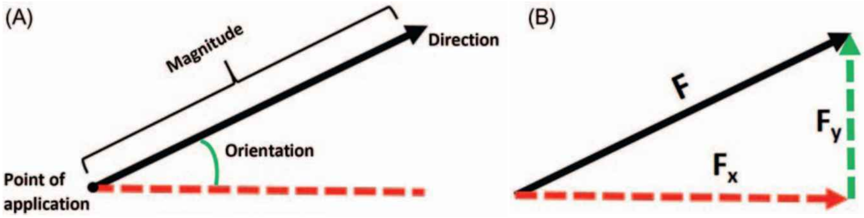

FIGURE 2.5 Vector. (A) Vector description (magnitude, point of application, orientation, and direction). (B) Vector components.

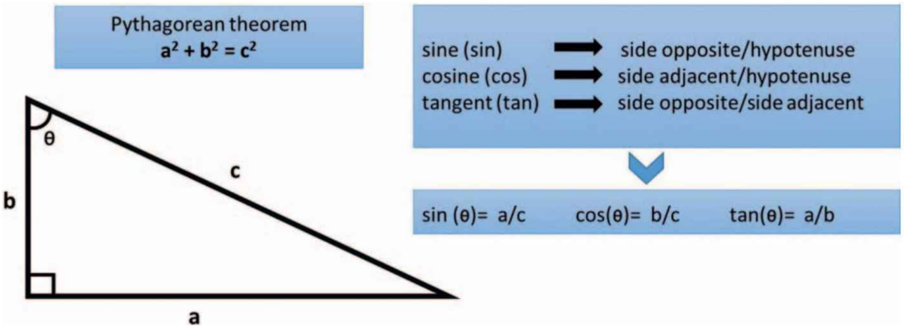
Pythagorean theorem
$a^2 + b^2 = c^2$
sine (sin) → side opposite/hypotenuse
cosine (cos) → side adjacent/hypotenuse
tangent (tan) → side opposite/side adjacent
sin (θ)= a/c
cos(θ)= b/c
tan(θ)= a/b
θ
b
c
a

FIGURE 2.6 Commonly used trigonometric relationships for right triangle in biomechanics.

on human body you must consider. In such situations, it is possible to a find out a single vector which could produce the same effect as produced by all the vectors being added. This single vector is resulting from a composition of two or more vectors is called a resultant vector (Oatis, 2004; Loudon et al., 2013; Hamill et al., 2015).

Trigonometric functions

One objective of biomechanics is to determine the vectorial quantities in the human body. Although the questions with vector quantities can be solved using either a graphic or a trigonometric approach, trigonometric approach gives more accurate results and it is less challenging. Trigonometry is a useful tool for vector resolution and vector composition process in biomechanics. Therefore, many concepts in biomechanics require usage of trigonometry.

Trigonometric functions deal with the relationships present between the distances (sides) and angles of triangles. Many functions in trigonometry are based on a right triangle (a triangle containing a right 90° angle). Fig. 2.6 illustrates the commonly used trigonometric relationships for right triangle in biomechanics (Oatis, 2004; Knudson, 2007; Hall, 2011; Neumann, 2013; Hamill et al., 2015).

Kinematics

Kinematics is the branch of classical mechanics that describes the motion of points, objects, and systems of groups of objects without considering the mass of each or the forces that caused the motion. From kinesiological perspective, kinematic is explored as the motions of human body properties. Translation and rotation movements are centered in the kinematics of human beings (Atwater, 1980; Houglum and Bertoti, 2012; Robertson et al., 2013).

Translational movement is the name given to the movement of body parts as a whole. In this type of motion, body parts move in the same direction parallel to each other. The axis of the movement may be along a straight line or along a curved line. Body parts are considered to be rigid. An example of this is the movement of the pelvis during dance. The pelvis moves in the same direction as the whole during the dance. The movement of the pelvis may be along a straight line or along an inclined line in accordance with the dance figure. In contrast, the rotation movement takes place along a circular path about an axis. Body movements are generally defined by their translational movement because they are defined according to the center of gravity of the body, just before the sacral second vertebra. Translational and rotational movement skates are also distinguished as active and passive movements. The active movements are caused by the muscles, while the passive movements are the movements that are caused by a factor other than the body. The angular values are used to define the rotational movements while the distance units are used to define the translational movements.

There is no specific axis of movement during translational movements, but in rotational movements there is the axis of motion. In the rotational movements, the axis of motion is given to where the degree of rotation is zero. The axis formed during rotation of a joint occurs within the joint and usually very close to the center. Kinematics are generally studied under two concepts. These are osteokinematics and arthrokinematics.

The term osteokinematic is in accordance with the principles of regulation of the aforementioned movement axes. There are three main axes and three main planes. If the knee joint flexion movement is given as an example, the femur and tibia bones are involved. If this movement is examined as osteokinematically, the movements of each of the bones can be evaluated separately or together. The movement can be defined as the movement of the femur on the tibia or the movement of the tibia on the femur. However, in terms of daily life activities, the segment where the movement takes place is called the primary segment.

If the upper extremity movements are considered in general, the movement of the distal segment occurs on the proximal segment. As an example to take any object on the desktop and put it in another place. This movement for example, as seen in the upper extremity movements, the distal segments move more, while the proximal segments act as more stabilization. In addition, the proximal segment acts on the distal, such as push pulling, where movement occurs more proximally.

In the evaluation of lower extremity movements, a general definition cannot be made as in the upper extremity. The distal segment can move on the proximal segment while the proximal segment can move on the distal segment as it can be a very important place in daily life. In the swing phase of the walk, the piston moves over the proximal segment of the proximal segment, while the proximal segment moves over the distal segment from the heel contact to the finger lift. If the stair stroke activity is examined osteocynematically, two different conditions arise. The distal segment moves on the proximal segment of the extremity while the local contact is cut and moved downwards, but the proximal segment moves on the distal segment as soon as contact with the ground begins. In rehabilitation evaluations, this situation of osteokinematic is defined as closed and open chain movements.

Closed and open chain motions are defined by the distal segment being in contact with the ground and still or mobile. Open kinematic chain activities refer to motions of the distal segment of the body are free. Moving the glass to the mouth can be regarded as an open kinematic chain activity. While a person performing closed kinematic chain activities; the distal segment of the body is fixed on ground and the proximal segment of the body is free to move. The squat activity may be given as an example of this chain. The term of closed kinematic chain is controversial. Health related issues covers only one extremity in this concept. On the other hand, according to the engineering disciplines both ends of the objects have to be fixed to regard the situation as a closed kinematic chain. For example, one leg squat is an open kinematic chain for engineering disciplines, because other leg is free (Aggarwal and Cai, 1999; Hamilton, 2011; Nordin and Frankel, 2012). Fig. 2.7 shows the examples of open and closed kinematic chain activities. In open kinematic chain, knee flexion may occur freely with or without motion at the hip and ankle joints. To put it more explicitly, motion at the knee is independent of hip and ankle motion. Knee flexion in squatting, closed kinematic chain, is accompanied by the motion of hip flexion and ankle dorsiflexion.

Arthrokinematics refer to the motions that occur between the articular surfaces of the joints. When joints move in arthrokinematics, three types of fundamental motions can occur between the joint surfaces: 1. gliding or sliding, 2. rolling, and 3. spinning (Andrews, 1983; Aggarwal and Cai, 1999; Houglum and Bertoti, 2012; Nordin and Frankel, 2012). In Fig. 2.8, all three of these motions at the joint level are shown.

Fig. 2.9 shows the illustration of three fundamental arthrokinematic motions using the motions of a car tire. Gliding is a linear motion in which the movement of one joint surface is parallel to the plane of the adjacent joint surface, such as car tire is gliding (skidding) along the ground. Rolling is an angular motion in which each point on a surface comes into contact new point on the other joint surface, such as car tire is rolling along the ground. Spinning is an angular motion in which the rotations of the movable joint surface on the fixed adjacent surface, such in spinning of car tire without changing location.

Kinetics

Force can be thought of as a push or pull acting on an object. Pushing on a stalled car may or may not move the car, depending on the direction and strength of the push, and the force of friction between your feet and the ground. Kinetics is the subdivision of mechanics that is concerned with the forces acting on a system such as any object, or human body. The kinetic movement analysis describes the causes of motion and investigates the forces causing a movement. If we take the example of volleyball sport, the possible kinetic variables during the activity are the forces between the ball and the hands, and the forces between the feet and the ground. Kinetic analysis is more difficult than the kinematic movement analysis because forces cannot be seen. There is no way of accurately investigating the force unless it can be measured with recording devices, because the force cannot observe visually.

Kinetic information is essential for improving human motion and performance. Kinetic analysis also identifies the important parts of a skill in terms of movement production. For example, a skill that involves vertical jumping is integral to successful spiking in the sport of volleyball. Therefore, the knowing that the amount of hip extensor, knee extensor, and the plantar flexor actions during vertical jumping is important for improving spiking performance in volleyball players. After kinetic analyses, you can answer following question: What is the best technique for maximizing a vertical jump in

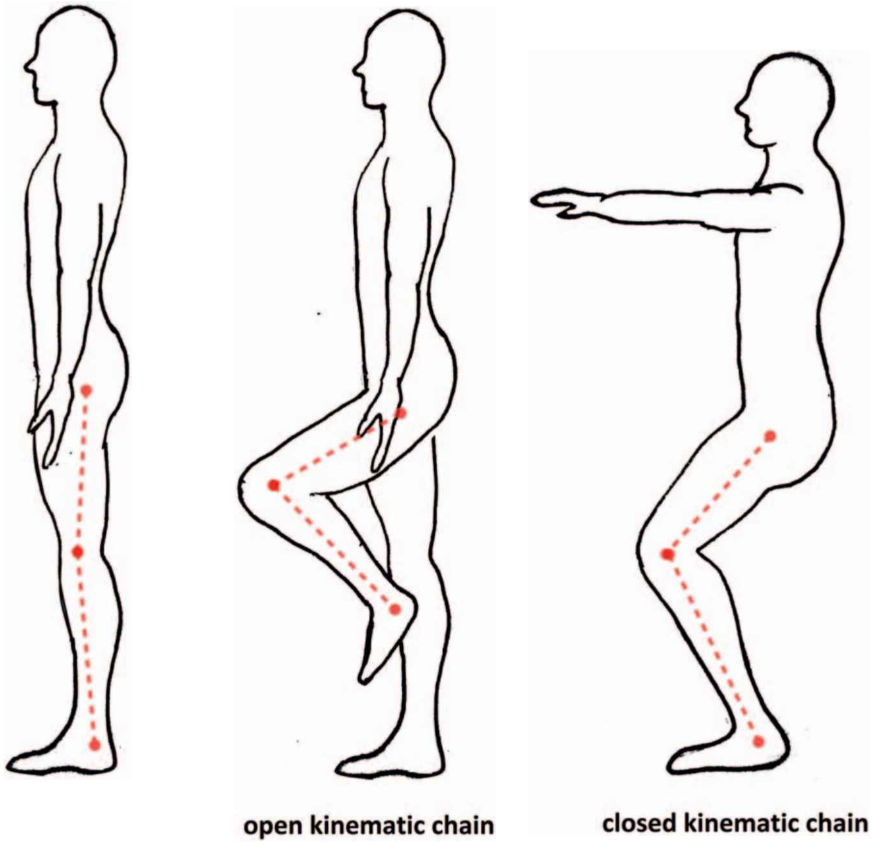

FIGURE 2.7 Closed and open kinematic chains. In illustration, knee flexion is shown with simultaneous motion at the ankle and hip.

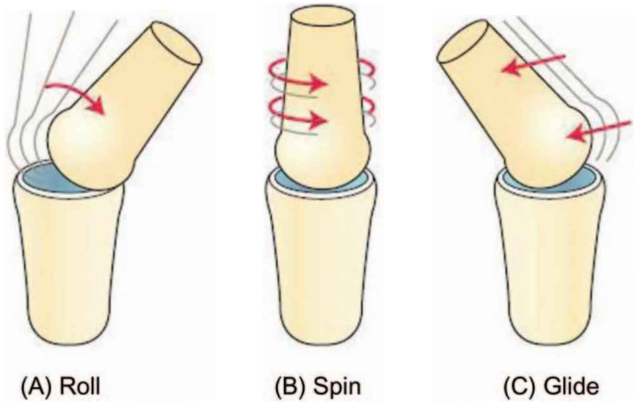

FIGURE 2.8 (A) Rolling of one bone on another; roll is an axial movement. (B) Spinning of one bone on another; spin is an axial movement. (C) Gliding of one bone on another; glide is a nonaxial movement.

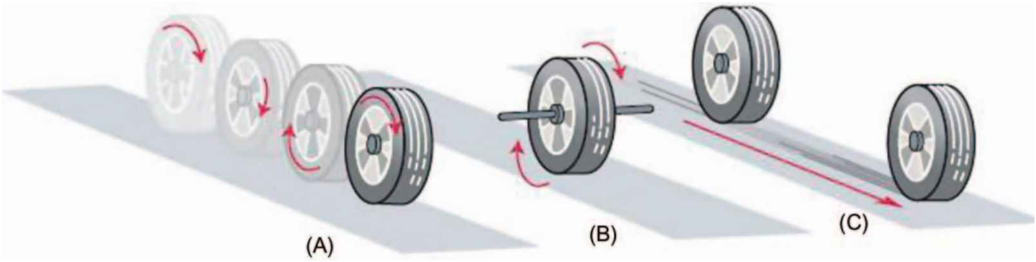

FIGURE 2.9 Arthrokinematic motions: roll, spin, glide, analogy of arthrokinematic motions can be made to a car tire. (A) Tire that is rolling along the ground. (B) Tire that is spinning without changing location. (C) Tire that is gliding/sliding (skidding) along the ground.

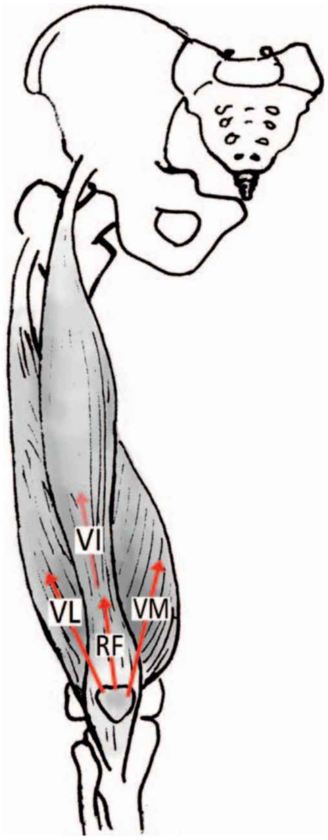

FIGURE 2.10 Illustrative schema of how the forces of the quadriceps femoris muscle act on patella during the contraction. VM: vastus medialis, VI: vastus intermedius, VL: vastus lateralis, RF: rectus femoris.

volleyball players and which muscles are especially important rehabilitation?

Kinetic analysis can provide valuable information to health professionals and researchers regarding the how a position or posture is maintained and how the movement is generated? For example, the poor body alignment in individuals with forward head and shoulder posture, leads to greater torque production by gravitational forces, which is being offset by greater internal forces generated by muscles around the cervical region and the shoulder. Changes in muscle activity may lead to musculoskeletal problems and increase the risk of injury. Therefore, kinetics play a crucial role in identifying the pathologic conditions and the injury risk of musculoskeletal system (Knudson, 2007; Houglum and Bertoti, 2012; Hamill et al., 2015).

The full understanding of all aspects of human movement is based on the analysis of both kinematics and the kinetics variables of movement and its relations to each other.

There are two important vector quantities at the origin of kinetics: force and torque (Knudson, 2007).

Forces

Force is a push or a pull that produces, modifies, or halts a movement. From a kinesiologic standpoint, force can produce movement, stabilizes the body and maintains the posture. Force usually expressed in pounds (lbs) or Newtons and the symbol of force is F (Knudson, 2007; Mansfield and Neumann, 2013).

As mentioned previously, force is a vector, and vectors can be physically represented or drawn as arrows. Components of force are: magnitude, orientation, direction and application point. Fig. 2.10 shows the quadriceps femoris muscle force acting on the patella in the frontal plane during knee extension. Quadriceps femoris muscle has four parts: rectus femoris, vastus lateralis, vastus medialis, and vastus intermedius. Therefore, directions of the pulling force applied to the patella by these four muscles can be drawn with four vectors.

Resultant force

Usually, more than one forces act on the human body or body segment simultaneously. When two or more forces applied to a segment are combined into a single resultant force (the vector sum of all forces), the magnitude of this new force is considered equal to sum of the component vectors (Nordin and Frankel, 2012; Neumann, 2013). Fig. 2.11 shows the resultant force that acts on patella during knee flexion. In the sagittal plane, the quadriceps femoris tendon force (resultant force of all quadriceps muscles activity) and the patellar tendon force combine to produce a resultant force vector directed posteriorly on the patella. This resultant force compresses the patella on the femur at the patellofemoral joint.

Types of forces

From a functional perspective, there are four types of forces according to the their primary sources: gravity, muscles, friction, and the externally applied resistances (Houglum and Bertoti, 2012).

Gravity

It is a force that attracts any objects with mass in the universe and therefore we can say that it is the most prevalent type of force among others. Gravitational force is commonly referred to as the "weight" of body, body segment, or any object. The terms of "weight" and "mass" are often used interchangeably, but they have not the same meaning. A mass is a measurement of the amount of matter object contains. The greater the mass, the harder the object is to move. It is measured in slugs or kilograms (One slug is equal to 14.59 kg). However, weight is the force of gravity acting on the object. It is equal to the mass of an object multiplied by the gravitational acceleration constant. The formula for weight is: W (weight) = m (mass) • g (gravitational acceleration constant, 9.81 m/s^2). The mass of any objects doesn't change (unless you remove some amount of matter it contains), but its weight can be changed according to the pull of gravity. Gravity is counterbalanced by the supporting surface on which a person is standing, lying, or crawling, that is to say, without surfaces such as a floor, chair, or bed on which to balance our weight, we would simply fall. This concept is called as Newton's third law of motion, which is discussed later.

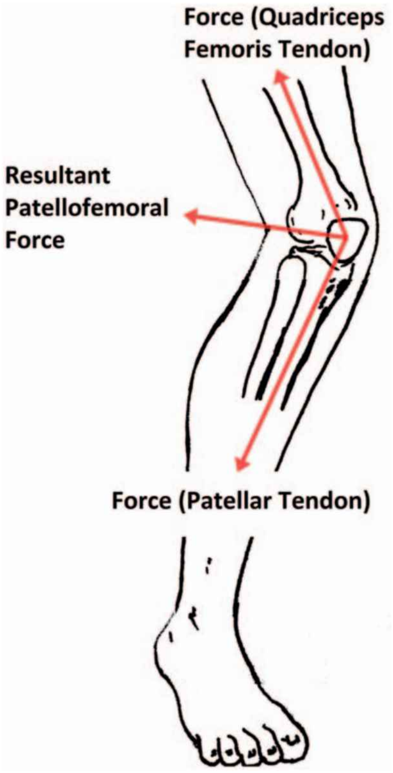
Force (Quadriceps Femoris Tendon)
Resultant Patellofemoral Force
Force (Patellar Tendon)

FIGURE 2.11 An example of the resultant force of the knee joint. Biomechanical model of the forces acting on the patella at the patellofemoral joint in the sagittal plane.

Muscles

A force produced by a muscle that provides motion or stabilization of body segments and of the entire body. Muscles produce forces on their bone segments by either active contraction or passive stretching. From a muscle and joint interaction perspectives, a force produced by a muscle that lacks a moment arm will not result in a torque or a rotation on the related joint or joints. Three types of activation of muscle (isometric, concentric, and eccentric) produce a muscle force (Fig. 2.12). The ability and the magnitude of muscle contraction depend on the contraction type, cross-sectional area, the structure of the muscle, and proportion of motor units basically.

Friction

The forces between two objects in contact are resolved into the 'normal reaction'' and 'friction'' (Fig. 2.13). The normal reaction is the force at right angles to the surfaces in contact, while friction is totally different from normal reaction. Friction is the force acting in parallel to the surfaces. In other words, it is the resistance to movement between two objects that are in contact with each other. Friction can be advantageous or disadvantageous. If friction is optimum, it provides stability; if friction is excessive, it makes the motion difficult and retardy; if friction is inadequate it leads to instability.

The force of friction (F) is equal to the product of the coefficient of friction (μ) multiplied by the normal reaction (F_N), if the two surfaces are dry ($F = \mu \bullet F_N$). The coefficient of friction depends on the texture and nature of the surfaces of two objects. For example, articular cartilage reduces friction between the joint surfaces. The coefficient of friction between the two joint surfaces

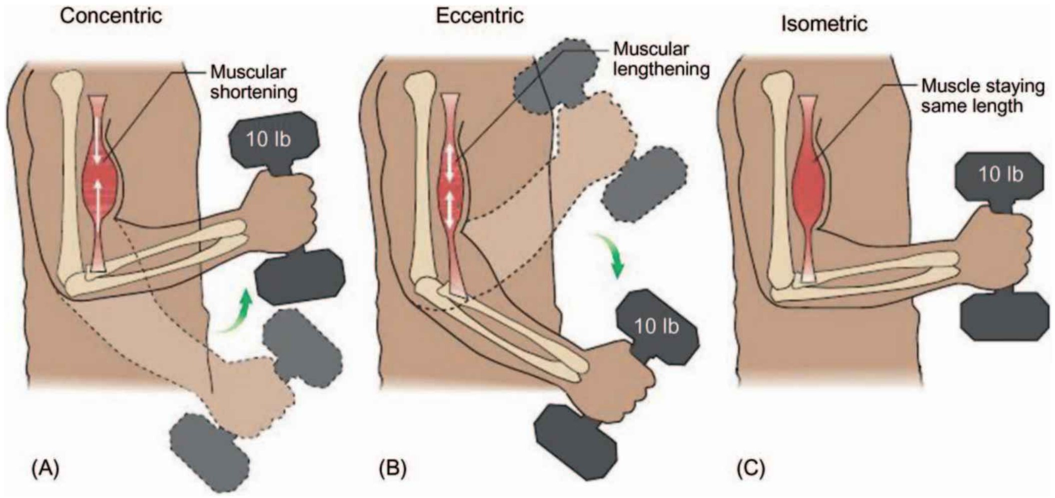

FIGURE 2.12 The three types of muscular activation. (A) Concentric. (B) Eccentric. (C) Isometric.

covered by articular cartilage and wet with synovial fluid is extremely low. For instance, the degenerative process of articular cartilage in joints with osteoarthritis has the negative consequence of joint function due to the increased friction. A decline in both concentration and molecular weight of hyaluronic acid reduce the viscosity and this is associated with an increase of friction.

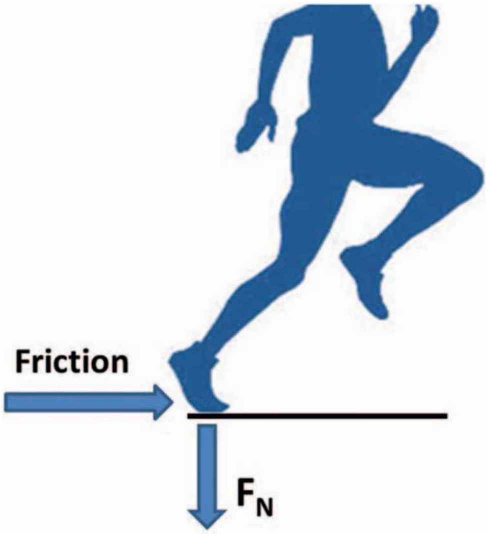

FIGURE 2.13 Forces of contact between objects. F_N: normal reaction and friction.

Externally applied resistances

Examples of externally applied resistances include free weights, exercise pulleys, manual resistance of a physical therapist, or doors (Knudson, 2007; Houglum, 2010; Houglum and Bertoti, 2012; Loudon et al., 2013; Mansfield and Neumann, 2013; Neumann, 2013).

Forces can be also classified as ‘internal forces’’ or ‘external forces’’ according to body. Internal forces are generated within the body. These forces may be active or passive. Active forces are generated by muscles, whereas passive forces are generated by tension in stretched ligaments, joint capsules, and intramuscular connective tissues. External forces (gravity, external loads such as a ball or a barbell, and manual resistance of a physical therapist) are arising from outside the body (Nordin and Frankel, 2012; Mansfield and Neumann, 2013).

Musculoskeletal system is subject to a variety of applied forces loaded in various directions. These loads can be produced by internal forces, external forces or weight bearing and these loads can move, stabilize, deform or injure the body segments. Compression, tension, bending, torsion, and shear are the types of forces or loads that acting on the musculoskeletal system (Fig. 2.14).

Compressive forces are collinear forces acting in similar directions. These types of forces push tissues together. Compressive forces are essential for healthy development

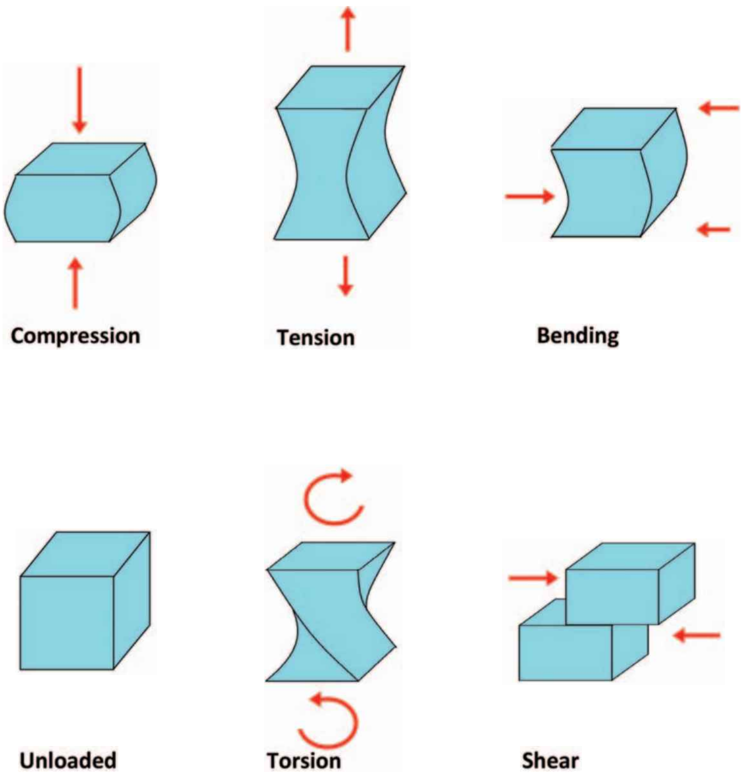

FIGURE 2.14 Different types of forces acting on musculoskeletal system.

and growth of the bone. In sports such as wrestling and rugby, cervical fractures can be seen when the compressive force is applied against the top of the head of an athlete (Loudon et al., 2013; Hamill et al., 2015).

Tensile forces are also collinear forces, but acting in opposite directions to pull the tissues apart. Avulsion fracture occurs when a portion of the bone at the insertion of the tendon is torn away due to the tension originated from muscle contraction (Loudon et al., 2013; Hamill et al., 2015).

Bending force involves the combination of tensile and compressive forces. When a non-axial force is applied to the tissue, concave side experiences compression while the convex side experiences tension. Bones of the lower extremity are regularly subjected to the bending forces caused by alternating compression and tension forces during gait (Nordin and Frankel, 2012; Loudon et al., 2013; Hamill et al., 2015). For instance, neonates and infants normally have varus angulation of the lower extremities. After they start to walking, it starts to change to valgus angulation. Therefore, any varus angulation at the knee joint after the age of 2 years is thought to be an abnormal (Cheema et al., 2003).

Torsional force occurs when one end of the tissue fixed and it subjects to the twisting at its longitudinal axis. It can occur in the lower extremity when the foot is planted and the body changes its direction. A spiral fracture is a result of torsional force (Nordin and Frankel, 2012; Hamill et al., 2015).

Shear forces are coplanar and opposite in direction but not collinear. Shear force is applied to parallel to the surface of tissue. Therefore, one portion of the tissue displaces in relation to other portions of the tissue. These forces are responsible for skin problems, such as blister, in which shearing takes place between the skins and underlying tissue (Nordin and Frankel, 2012; Loudon et al., 2013; Hamill et al., 2015).

Torque

The ability of force to produce rotation about an axis is referred to as torque or moment of force. It is symbolized M for moment of force or T for torque. Torque equals the product of the force magnitude (how strong the force is) and moment arm (or torque arm). The moment arm is the perpendicular distance from the line of action of the force to the axis of rotation. Mathematically, torque is:

$$T(\text{torque}) = F(\text{force}) \times r(\text{moment arm})$$

If a force is applied to an object that is not on line with the center of the object, the force cause a torque that tends to rotate the object. No torque is produced if the force is applied in the direction exactly through the axis of rotation. In rehabilitation, isokinetic dynamometers are good example for devices that measure the joint torques.

A muscle creates or controls a movement through the development of torque. During any movement, both force and moment arm of muscle are changing depending on the line of pull of the muscle relative to the joint. An increase in the length of the moment arm of a muscle anywhere in the movement increases the torque produced by a muscle. On the contrary, if the moment arm decreases, more muscle force is required to produce the same torque around the that joint. For example, if you apply manual resistance on the tibia just above the ankle joint to resist the knee extension of your patient, your torque is less (or you have to produce more force for the same torque) than if you positioned your hand on the middle of the shank, your effort is more for the same torque production because your moment arm is shorter. Briefly, torque can be altered by changing the magnitude of force and moment that are useful managements in assessment and rehabilitation (Knudson, 2007; Houglum, 2010; Hamill et al., 2015).

Center of gravity

Gravity is a force which affects everything on the earth. So we have to understand the force of gravity and its effect to be able to evaluate its influence on the body and its segments during motion.

The center of gravity (COG) is the point where all parts of the body are equally distributed; it is the point where the weight vector starts. Whereas the center of mass (COM) is the point where the mass of the body is theoretical evenly distributed and balanced. In other words, the COM is exactly the point, where the body could be balanced in any direction. Although these two terms are used interchangeably, they differ in that way that the center of gravity is the direction in which gravity acts. But the center of mass does not refer to a vertical orientation and because of this, it has not a vector. Since you can balance most time an object at the COG, COG and COM are widely used as synonymously.

For the entire upright human body, the COG and the COM are the same points and it is located slightly anterior to the second sacral vertebra. Depending on the movement, the COM is continually changing during motion.

The information related to the COM of the human body and body parts is mostly derived from cadaver studies. But also mathematical modeling studies and imaging techniques such as computed tomography and magnetic resonance imaging contribute to the information regarding COM of different body parts.

If the object is symmetrical, the COG is easier to find and occurs in the geometric center of the object. But in asymmetrical objects, the COG can even be outside the mass. The same is valid for the human body.

The COG of an object is the sum of the COGs of each part of that object. The same is valid for the human body. Each part of the human body has his own COG and the general COG is driven from the calculation of these partial COGs (Clippinger, 2006; Houglum and Bertoti, 2012; Neumann, 2013; Hamill et al., 2015).

If the human body is in an upright anatomical position, the COG in an adult human body will be just anterior the second sacral vertebra (Braune and Fischer, 1984) or approximately 55% of a person's height (Hellebrandt et al., 1938). But if the human body is in an asymmetrical position like a whole body reaching, the COG will shift from the base of support and will occur outside the mass.

Variations on body height, proportions, and weight distribution will also lead to COG location differences. Also, gender differences will change the location of COG. For example, men have their COG usually slightly higher because women tend to have broader hips, while men have broader shoulders (Clippinger, 2006; Houglum and Bertoti, 2012; Neumann, 2013; Hamill et al., 2015).

Free body diagram

To analyze any human movement, it is important to take all forces into account, which acts on the system. Internal forces are not represented in these diagrams and external forces are those which are exerted outside the system but impact the system. That means all external forces related to the body must be considered and put in the analyses. But that is not easy. To facilitate the action of forces analyses, all forces which impact the body and movement are reflected in a simple diagram, called free body diagram or space diagram. A free body diagram is a basic figure of the system, which shows the forces as vectors and simplifies the analyses. These diagrams can be drawn for one part of the body or the whole body with objects which are important, regarding the extent of the analyses. The most important part of such an analysis is to define the forces in the system correctly which directions of the vectors.

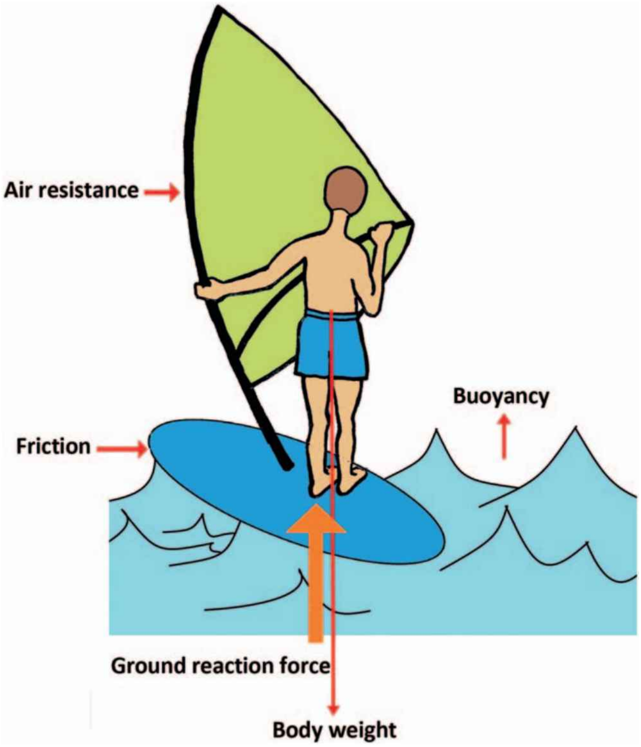

FIGURE 2.15 A free body diagram of a windsurfer.

Fig. 2.15 shows a free body diagram of a windsurfer from the total body coronal plane view. As seen in this diagram, all forces affecting the movements of the windsurfer are reflected in a basic way, which allows us to see all forces and account them into the analyses. There are numerous external forces acting to the human. But it is important to identify the main forces and put them in the diagram. At our sample, the main forces affecting the windsurfer are the own body weight of the surfer, which reflects the gravity, the ground reaction force (GRF), the friction between the board and the water, the air resistance, and the force of the water buoyancy. At the mentioned figure only main external forces are drawn, with the estimated location of the applicate force. If the athlete would carry a device at the back or wrist, an additional force which shows the weight of this object would need to represent in the diagram. In this case, a full body diagram is embodied, with the external forces which affect the total body. If the aim would be only a specific part of the body, then it has to be clarified which forces are affecting the related body part and have to be noted in the drawing. The related body part has to be isolated from the rest of the body for analyses purposes. The muscle forces which cross proximal and distal joints of specific segment have to be taken as external forces (because they are external to system) and have to be noted in the diagram. As mentioned before, it is impossible to account all of the forces acting the body part, like all the muscle groups affecting the joint. Because of that, the sum total of all muscle forces is considered and represented with a single force vector, reflecting the direction and magnitude during movement. In these situations, mostly the net muscle forces and joint reaction forces acting to the related joint are unknown and have to be calculated. And additional forces in the soft tissue like forces of the tendons, ligaments and air resistance are supposed to be ignorable.

Once the forces to the total body or related body part are identified, a free body diagram is very helpful to make the biomechanical analyses and therefore is recommended to be used for any movement analyses (Houglum and Bertoti, 2012; Neumann, 2013; Hamill et al., 2015).

Newton's laws

First law (inertia)

Newton's first law defines the inertia and often stated as 'An object at rest stays at rest and an object in motion stays in motion with the same speed and in the same direction unless acted upon by an unbalanced force'. In the body, active assistive range of motion exercises can be a good example for this law. It is difficult for a weak muscle to initiate the movement, because the muscles first need to overcome the inertia, but once the movement begins, it becomes easier for the muscle to continue the movement.

Second law (acceleration and momentum)

The second law states that the acceleration of an object is directly proportional to the force causing motion and inversely proportional to the mass of the object being moved. The change in velocity (Acceleration) depends on the mass of the object. The amount of motion is called as Momentum. The formulas used to calculate acceleration and momentum is below:

Momentum = mass × velocity
Mass = weight/acceleration due to gravity
Linear velocity = distance/time

Newton's second law of motion explains why a slow motion requires more strength than a quickly performed one. Thus, it is logical to employ slow, controlled movements in order to strength the muscles

Third law (action-reaction)

The third law states that an object reacts to a force with a force of equal magnitude in the opposite direction. The loading of the lower extremity joints while walking can be an example to understand this law. When the feet contacted to the ground, ground generates a force in the opposite direction (towards body) with the same amount (body weight). Therefore, it is recommended to perform walking exercises in shock-absorbing surfaces in order to decrease reaction forces towards joints. This law is also important to injury prevention, especially during a jump landing. A correct landing technique decreases the reaction forces and helps to prevent injuries (Houglum, 2010; Herman, 2016).

Levers

With the help of the levers, it is ensured that the rotational effects, called torque, are derived from linear directional forces. Levers are tools transmitting the force and converting the force into a torque. Essential components of levers are (1) rigid structure of a point (pivot), (2) the fixed fulcrum axis connected with the resistive load (weight), (3) the fixed fulcrum axis connected with the force applied. In addition to performing daily living activities, maximum activity is required with minimum effort during this activity. When the power generated by the muscles is transferred to the joints, the force generated along the long axis of the muscle can create a rotational force in the joint. Lever arms are an effective tool for forming and transmitting these forces. The joints form the axis of the movement during power transfer, while the muscles produce power to create movement within this axis. Lever arms increase the force produced by the muscles, as well as transfer the force to the distal part in a more controlled manner. In this way, the maximum capacity be reached with minimum effort with the help of the levers. The distances of the external and internal forces acting on a joint are called the force arm for internal forces and the load arm for external forces. As an example of the internal forces, the muscles can show the distance of the attachment point of a muscle to the force arm, while the distance of the load from the insertion is called the load arm. From this point of view, the work carried out on a joint varies in proportion to the length of the load arm as well as the amount of the load. The lever arms are divided into three classes. These are 1st class, 2nd class and 3rd class levers.

First class lever

In this type of lever arm, the load and force are acting in the same direction. The load and the force create opposing forces. As can be seen in the figure, there is a pivot point in the middle of the load and force. The extension of the load arm will create a mechanical disadvantage. In human body, neck extension may given an example. Atlanto-occipital joint is the fulcrum. Head weight is load and neck extensors are acting as a force arm (Fig. 2.16).

Second class lever

This type of lever arm is located between the force and the pivot point. As can be seen from the figure, the force is advantageous in this lever arm. In other words, less effort can be made for the force to be obtained. The most typical example of this lever arm is on the ankle. The amount of force that the triceps surae muscle has to create is less than the load. This mechanical advantage can also be given as an example of wheelbarrow. Because the force arm is further away from the pivot point, it is easier to carry a load with a wheelbarrow. Another example of the human body is the push-ups. When the examination position is taken, the pivot point is to have the toes at the

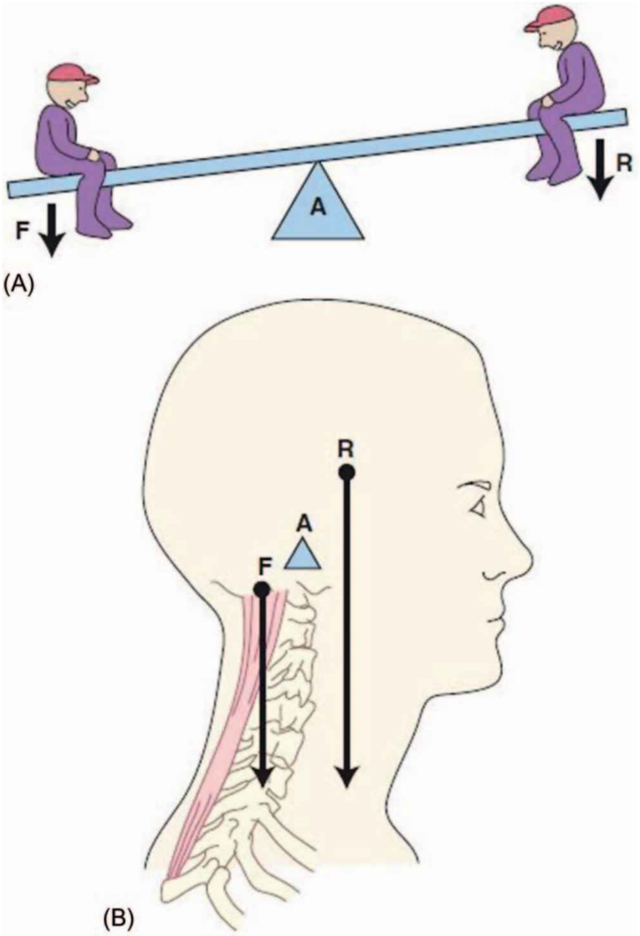

FIGURE 2.16 First class lever example. (A) A boy sitting at one end of a seesaw creates load (F) and a boy sitting at the opposite end creates reactive force (F). B) Head weight (R) is balanced by reactive force (F) exerted by neck extensor muscles.

level of the great sacral vertebra and the force is transferred from the arms. The muscles forming the Internal Force are pectoralis major and triceps brachii muscle (Fig. 2.17).

Third class lever

In human, most of the joints are similar to the 3rd class lever system (Fig. 2.18). In this lever type, the force is between the load and the pivot point. It is a mechanically disadvantaged lever type. In this lever type, more work is needed for similar workload. As can be seen in the figure, this type of lever system is included in the elbow joint and some of its most functions. If the elbow joint is considered, the pivot point is located in the olecranon, the force arm is located in the tuberosity as the insertion of the muscle, and the load arm is located more distally. In this lever type, as the distance of the force arm to the pivot point decreases, the rotational force generated by the muscle may decrease.

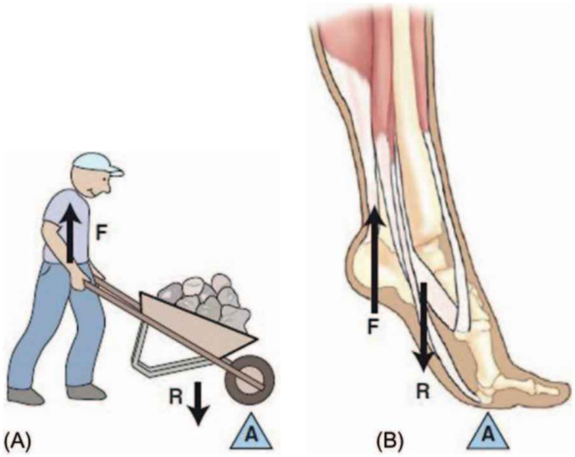

FIGURE 2.17 Second class lever example. (A) A worker lifts (F) handles for carrying a load (R) with a wheelbarrow. The axis of wheel represents fulcrum. (B) Rising body weight (R) on the metatarsal heads (fulcrum) needs force (F) exerted by triceps surae muscle.

Equilibrium

Equilibrium means that the sum of the forces acting on any object is zero. The equilibrium status can be instantaneous for the object. If the object is not permanently fixed, it may also be equilibrium. Equilibrium status is described in two types.

In the case of neutral equilibrium, the body can also maintain balance in the new state while it is moving. The body has taken a new position and the center of gravity is controlled within the equilibrium limits. In terms of the body, when a condition that disrupts the balance will occur, equilibrium will provide a new balance state by holding the body center of gravity on the support surface and at the moment when the forces are equalized.

If it is not stable equilibrium, the center of gravity will be kept on the support surface similar to the neutral equilibrium. This will find the new balance of the body with the potential energy that arises due to the position of the center of gravity of the various object or body. Potential energy and factors that disrupt the body balance will be eliminated. In the unstable medium or conditions, an unstable joint is formed when it cannot be tolerated. In this case, the potential energy of the center of gravity relative to the distance from the ground, and the support surface is narrow when the forces on the body will not be equal. If this condition continues, a new posture is needed to maintain the balance of the body. With the body getting a new posture, the center of gravity is brought to the support surface. After the deterioration of the static

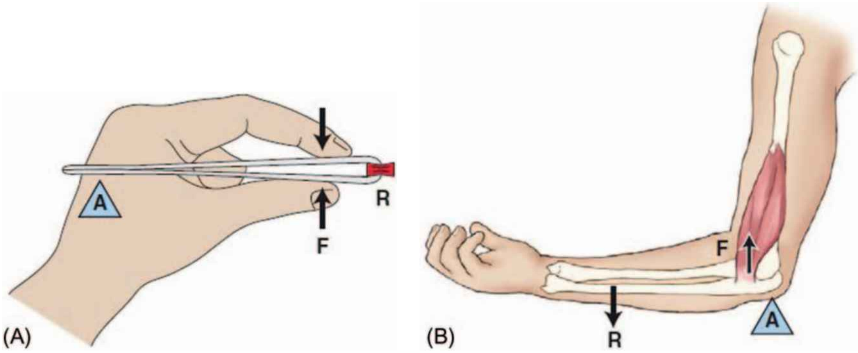

FIGURE 2.18 Third class lever example. (A) Thumb and index finger exert force (F) on a pair of tweezers to hold a cube (R), (B) Biceps brachii muscle exerts reactive force (F) to lift weight of the forearm (R).

equilibrium all the reactions to the new equilibrium state is called dynamic equilibrium.

Static and dynamic display status is transitive. Dynamic status is more common in activities such as walking, running, and jumping (Winter, 2009; Sylos-Labini et al., 2014; Özkaya et al., 2016).

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Chapter 3

Fundamentals of human movement, its control and energetics

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How does a purposeful movement start?

Evidences show that the brain represents multiple environmental and body-related features to compute transformations from sensory input to motor output. However, it is unclear how these features interact during purposeful movement (Desmurget et al., 1998; Barany et al., 2014). However, purposeful movements are executed consciously under the control of the brain, in contrast to rhythmic and automatic behaviors (in some conditions initiation of automatic behaviors occurs in the brain). For executing the purposeful movement, the nervous system needs to collect information from both our environment and inner body, evaluate this information in order to create a motor command and this motor command need to be transmitted to the effector organs. For instance, to hit a tennis ball, the nervous system needs to know how the ball is coming from the opponent and where it will locate on the court relative to player's own body (Desmurget et al., 1998). According to this information, the player needs to decide which stroke to perform (forehand, backhand, topspin, slice etc.) and how the body should take its position to perform the selected stroke effectively. All this process is planned in the brain and the integrative motor command is transmitted to the relevant effector organs located in both upper and lower extremities.

Neural control mechanisms of reflex and purposeful movements

Many structures and systems are working in a coherence to modulate other body systems and to execute fine motor movements in human body. For maintenance of both vital and daily activities, the nervous system collects proper sensorial information to produce proper motor responses. This information is collected via receptors, which are able to convert different types of stimulating agents (i.e. chemical, light, pressure, heat, touch) in to the signals understandable by the central nervous system. After decision making processes of cerebral cortex, motor system carries information from central nervous system to the muscles thorough descending (efferent) tracts (Schwartz, 2016).

Nervous system consists of central nervous system (brain and spinal cord), the peripheral nervous system (somatosensory systems and motor systems) and the autonomic nervous system (regulates vital activities such as heart rate and breathing). What really makes the nervous system difficult to understand from any other functional system in the human body is the complexity of the neuronal interconnections in the brain. It is estimated that we have 70–125 billion neurons, each of them branching 10,000 inputs and generating approximately 10^{14} synapses (Azevedo et al., Kandel, 2000; Ullian et al., 2001; Noctor et al., 2007) in which their function decreases with age (Madden, 1992) and differs in genders (Pakkenberg and Gundersen, 1997).

There were two earlier theories trying to explain how the nervous system works; (i) phrenology theory and (ii) aggregate field theory. Phrenology theory was proposed by two doctors, Joseph Gall (1758–1828) and Johann Spurzheim (1776–1832). Their theory primarily focused on measurements of the human skull and their relations with personality characteristics. Despite it is seen as a pseudo-medicine today it has taken part in popular culture during 19th century (de Souza et al., 2017).

Aggregate field theory basically means that all areas of the brain participates in all kind of movements. Prevalent view expressed by mainly Washburn (1916), Watson (1920) and other scientists for movement sequence was the execution of movement occurs in a

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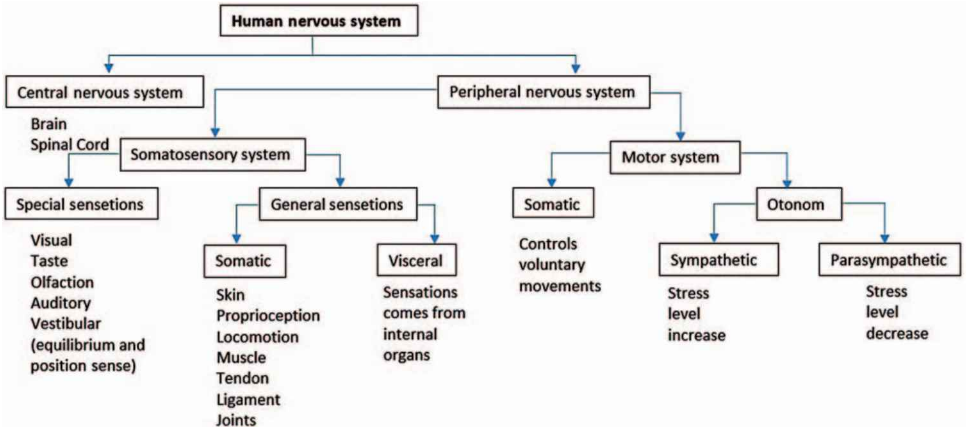

FIGURE 3.1 Integrative scheme of the human nervous system.

reflex chain hierarchically. This means stimulation of movement n activates movement n + 1, stimulation caused by movement n + 1 activates movement n + 2, and so forth. In other words, when the first movement occurs in a sequence, the sensory feedback systems inform the central nervous system about the changes detected via receptors and this information initiates the queued movement. It was the common idea until the middle of 20th century (Rosenbaum et al., 2007). But, in 1951, Karl Lashley challenged this view with his classic paper "The Problem of Serial Order in Behavior" (Lashley, 1951). Lashey provided some evidence that movements can occur even if the sensory input retards, some movements occur too quickly to follow all the sequences and brain creates internal plans for the next steps (Rosenbaum et al., 2007).

Before complex details, it is better to understand overall structures and functions of the nervous system. Fig. 3.1 illustrates the integrative scheme of the Human Nervous System.

The nervous system is divided into subcategories as; (i) the central nervous system and (ii) the peripheral nervous system. Peripheral nervous system has two further main components; the visceral (autonomic) nervous system and the voluntary (somatic) nervous system. This chapter will focus on voluntary nervous system, which execute and control purposeful movement patterns.

Central nervous system

Motor cortex

The central nervous system, especially prefrontal cortex of the brain, has a critical importance for controlling voluntary movements. As its name obvious for its function, the central nervous system is the *"center"* to which somatosensory systems provide sensory information and from which motor system transmits motor output to the muscles. Although prefrontal cortex has a major function for planning and controlling of somatic movements, it is not the merely structure for programing and releasing specific motor commands following decision making. Coordination of some other subcortical areas such as basal ganglia, thalamus, cerebellum and brain stem (pons, medulla oblongata, reticular formation) is needed for the execution of fine motor movements. Table 3.1 illustrates three important areas located in the motor cortex.

Basal ganglia

Beneath the cerebrum, there are five pairs of nuclei interconnected to each other. Located close to the thalamus, these five pairs of nuclei comprise the basal ganglia (Globus Pallidus (externus, internus), Putamen, Cuadate Nucleus, Subthalamic Nucleus, Substantia Nigra). Basal ganglia play an extremely important role for fine tuning of goal-directed movements. It acts as a modulator and facilitates the execution of movement by showing exhibitory/inhibitory effects via both direct and indirect pathways (Table 3.2)

Information flow in direct pathways occurs (i) from motor cortex to putamen, (ii) from putamen to globus pallidus internus, (iii) from globus pallidus internus to thalamus and (iv) from thalamus to motor cortex. On the other hand, information flow in indirect pathways occurs (i) from motor cortex to putamen, (ii) from putamen to globus pallidus externus, (iii) from globus pallidus externus to subthalamic nucleus, (iv) from subthalamic nucleus to globus pallidus internus, (v) from globus pallidus internus to thalamus and (iv) from thalamus to motor cortex. Direct pathways are shorter compared to indirect pathways, do not visit the subthalamic nucleus and generate an exhibitory effect. Whereas indirect pathways are structurally longer, visit the subthalamic nucleus and generates an inhibitory effect. Besides, the activity of the nuclei consisting of basal ganglia differs in resting and movement conditions.

As an important concept, all motor plans that include multiple movements basically stored in basal ganglia and cerebellum. In real world conditions, movements occur in

TABLE 3.1 Important movement-related areas of the motor cortex.

Name	Location	Function
Primary Motor Cortex (M1)	Lying along to the central sulcus	Generation of neural impulses to control the execution of somatic movements
Supplementary Motor Cortex (SMA)	Lies medial to the premotor area, also forward of the primary motor cortex	Coordination of two-handed movements, also planning of complex movements
Premotor Cortex (PMA)	Lies just immediately anterior to the primary motor cortex	Not uniform in function, primarily selection of the movement sequence based on external events

TABLE 3.2 Important movement-related areas of the basal ganglia.

Name	Location	Function
Globus Pallidus (externus, internus)	Beneath the motor cortex, close to midline and thalamus	Internal part transmits information from putamen to thalamus, external part transmits information from putamen to subthalamic nucleus
Putamen	Beneath the motor cortex and lateral to globus pallidus	Transmits information from motor cortex to globus pallidus internus and externus
Cuadate Nucleus	Laterally locates beneath the motor cortex and encircle globus pallidus and putamen	Constitutes striatum with putamen, has multiple functions related with both basal ganglia and limbic system
Subthalamic Nucleus	Medially located to globus pallidus and just beneath the thalamus	Transmits information from globus pallidus externus to globus pallidus internus
Substantia Nigra	Beneath the globus pallidus and really close to midline	Transmits information from motor cortex to putamen, release dopamine for both exhibitory and inhibitory functions

the sequence as follow. For instance, if you want to put a chocolate bar into your mouth, you need to perform multiple movement patterns (i.e. extending your arm forward, grabbing the chocolate bar using fingers, putting the chocolate bar into your mouth, chewing and swallowing). Once the idea of the movement has created in prefrontal cortex, this information is sent down via motor cortex to basal ganglia and cerebellum for checking. Then, it needs to be conveyed to motor cortex again passing thorough the thalamus. In some conditions, someone might think to perform a movement, but they do not really perform it. Even in such conditions, basal ganglia start to increase its firing rate. In other words, basal ganglia have electrical activity even before the movement really starts (Enoka, 2008).

Cerebellum

Interactions between basal ganglia and cerebellum were thought to occur primarily at the cortical level. However, newly identified pathways using virus tracing method provide a direct route for cerebellar activity to influence and be influenced by basal ganglia activity (Bostan and Strick, 2010) Cerebellum is the major balance and postural control center that provides best possible posture with stabilization of head and body posture, the coordination of both voluntary and automatic movements and the control of gaze, using combined eye and head movements.

The cerebellum corrects the errors in each purposeful movement comparing output and planned action based on input from motor, somatosensory and parietal association areas (Flament and Ebner, 1996). As a storage of the huge template of different patterns of voluntary movements, cerebellum imparts the previously stored pattern that best fits to planned action. To do this, cerebellum calculates how much the arm should be extended to reach the chocolate bar, and how wide the fingers must be opened to grab it. Coordinating the timing and force of different muscle groups to produce these fine movement on precise trajectory (Koziol et al., 2014), cerebellum calculates amount of motor unit to be fired to create sufficient muscle force on time for providing friction between fingertip and chocolate bar to hold it.

Peripheral nervous system

Peripheral nervous system has two main components as: the visceral (autonomic) nervous system and the voluntary (somatic) nervous system.

Autonomic nervous system deals with body regulator activities such as blood pressure, heart rate, body temperature, glandular function etc. The Autonomic nervous system also can be divided into three subdivisions as: (i) sympathetic (regulates body functions when we are under stress), (ii) parasympathetic (regulates body functions when we are in a relaxed condition), (iii) enteric (a complex neuronal network within the walls of the gastrointestinal system), which attracts attention by emphasizing the strong brain-gut relationship with recent studies (Seira Oriach et al., 2016). But this chapter focuses only on voluntary movements and how all systems are working in a harmony to execute and control its modulation.

We previously mentioned that one of the main duties of the nervous system is to collect information from both our environment and inner body. This information is perceived via special components (receptors), transmitted to central nervous system via micro-cables (neurons). Receptors receive sensory information and convey this information via neurons and synapses to the brain throughout ascending (efferent) pathways (to the spinal cord also if the action is a reflex). In the following section, we go into details of somatosensory systems that is responsible to bring signals to brain from both our environment and inner body for the execution of voluntary movements.

Neurons

Nervous system maintains a perpetual communication between body systems and central nervous system even under unconscious conditions. Neurons and synapses can be regarded as building blocks of the entire system. They receive and send signals via action potentials, which occur after reaching a certain threshold.

Despite their structural similarities (cell body, many dendrites, an axon), neurons show also a great variation in size and shape according to their function and location in the human body (Table 3.3). Being located in the central nervous system, they are supported by other special cells called *glia* or *glial cells*.

Synapses

Synapses are connection points between neurons. Even though the axon of one neuron is quite close to the other neurons' receptor surfaces (postsynaptic) they locate without having any physical contact. The transmission of electrical activity propagates from presynaptic to postsynaptic neuron via mostly chemical mediators (neurotransmitter). Electrical activity at the end of the axon of presynaptic neuron leads to release neurotransmitter into the synaptic cleft from vesicles. Receptors of postsynaptic neuron detects neurotransmitter and prepares either exhibitory or inhibitory responses effecting the postsynaptic neuronal activities.

Somatosensory systems

The role of somatosensory systems is to provide sensory feedback to the central nervous system continuously. As a part of peripheral nervous system, somatosensory systems are also divided into two subcategories as; (i) special sensations and (ii) general sensations. While special sensations are dense in one part of the body (i.e., photoreceptors on

TABLE 3.3 Functions and structures of different type of neurons.

Name	Structure	Function
Sensory Neurons	Linear in shape, have a single axon which sensory receptor ends to the cell body	Receive information from sensory receptors and transmit this information to central nervous system
Alpha Motor Neurons	Dendrites locate in the spinal cord, have many dendritic branches, their axons are relatively long	Innervation of muscle fibers (extrafusal), the number of the innervated skeletal muscle fibers can vary between 100 and 15,000
Gamma Motor Neurons	Smaller and less-branched axons than alpha motor neurons, dendrites locate in the spinal cord	Innervation of contractile muscle fibers (intrafusal) located in muscle receptors
Pyramidal Cell Neurons	Their dendrites resemble to a pyramid, locate in motor cortex	Sending motor commands from motor cortex to spinal cord, their axons can reach up to 1 m in length
Purkinje Cell Neurons	Locate in the cerebellum, have a special tree-like shape, their numerous branching dendrites show an organized structure	Regulate and coordinate voluntary movements that mostly no need to reach conscious level, control final output of motor coordination, provide inhibitory feedback to deep cerebellar nuclei
Interneurons	Many dendrites and branching axons, vary in size and shape, locate in brain and spinal cord	Facilitates the transmission of the information, based on the intensity of the stimulus they can also play a decision making role particularly in case of reflex arch

retina, taste receptors on tongue), general sensations can be found multiple areas of the body (i.e., proprioceptors in all skeletal muscles). But, the density of general sensations also varies in different parts of the body. For instance, cutaneous receptors are more densely state on fingerprints and plantar region of the feet and their damage can lead to decrease in motor performance due to lack of sensory input to the central nervous system (Abernethy et al., 2012).

The function of all receptors, like transducers in electronics, is to convert physical energy into coded nerve impulses. Converted electrical signals are carried to the central nervous system via afferent (carrying information from environment and inner body to central nervous system) and reach to the effector organs via efferent (carrying information from central nervous system to effector organs) fibers. Central nervous system is unable to send proper motor commands for goal-directed movements unless it receives feedback. In this vast communication network, motor commands sent from cortical and subcortical centers to the spinal cord via cranial and spinal nerves (called also upper motor neuron) and from there to the muscles for voluntary movements via alpha and gamma motor neurons (called also lower motor neuron). While the afferent (sensory) fibers enter to the spinal cord via the dorsal (posterior) root ganglia, the efferent (motor) fibers leave the spinal cord via the ventral (anterior) root ganglia.

The somatosensory systems process information by using both general and special somatic sensation (i.e., visual, auditory, temperature, vestibular, touch, proprioception). Vision and proprioception are two main sources of sensory information for controlling voluntary movements. Visual information has dominancy over other types of sensory information which means when there is conflict about the body position, our nervous system tends to rely on visual information (Lee and Thomson, 1982).

Humans, like all other kind of mammalians, are specialized to perceive sensations in a limited range. For instance, human ear is sensitive to audio frequencies between 20 and 20,000 Hz. Besides, when a somatosensory receptor is stimulated either naturally or artificially, the sensation perceived by the receptor is the same to the information processed by the receptor under normal conditions. That is, if the characteristics of the stimulation are a vibratory stimulation, other types of somatosensory receptors (i.e., temperature sensitive) will not respond to this stimulus and this concept is valid for all different types of receptors.

Cutaneous receptors (mechanoreceptors)

In contrast to special sensation receptors, general sensation receptors are scattered all over our body. Skin receptors (known as mechanoreceptors and cutaneous receptors also) enable us to detect the location of the stimulus when an outer force (i.e., touch, pressure, stretching, vibration, motion) applied and deformed our skin (Table 3.4) Each of the receptors is sensitive a specific type of stimulus. For instance, the density of the corpuscles, which are sensitive to touch, is high on fingerprints and sole of the feet.

Another important phenomenon of the receptors is adaptation. Particularly, hair follicles, pacinian corpuscle and meissner corpuscle are able to show a rapid adaptation. This adaptation property of the receptors is really beneficial for our nervous system. Otherwise, the nervous system will be bombarded with insignificant information such as the pressure applied by our clothes. Since receptors provide information about the mechanical changes,

TABLE 3.4 **Locations and functions of mechanoreceptors located in cutaneous tissue.**

Name	Location	Function
Ruffini Corpuscles	Deep part of the skin but superficial to pacinian	Perceive light touch as a part of discriminative touch system, sensitive skin stretch receptors
Pacinian Corpuscles	Deep part of the skin, subcutaneous tissue under epidermis	Perceive crude touch and high-frequency vibration stimulus (100–300 Hz), particularly onset offset times of these stimulus
Meissner Corpuscles	Locates in epidermis tissue, hairless skin (i.e., palms of the hands, plantar area of the feet)	Creates fast adapting signals against sustained mechanical force, they are sensitive to low-frequency (30–50 Hz) vibration stimulus
Merkel Complex	Locate in basal layer of the epidermis, both hairy and hairless skin	They have fine tactile receptors as a part of discriminative touch system, helps identifying the shape and form of objects
Hair Follicles	They found all over the hairy skin in contrast with Meissner Corpuscle	They are sensitive against movement changes as a part of discriminative touch system, give information about direction and velocity of the movement
Free Nerve Endings	Found many parts of the somatosensory system such as muscles, tendons, joints, cornea, the visceral organs, etc.	They are able to perceive many type of stimulus but considered to be the highly sensitive for crude touch, pain and temperature

in the presence of continuous stimulus, the frequency of action potentials supplied by afferent fibers decrease quickly and stop.

Proprioceptive receptors

Proprioceptive receptors are located in profoundly in muscles, tendons, joint ligaments and joint capsules. Muscle spindles, golgi tendon organs and joint receptors provide sensory information to the central nervous system about the spatial position of the body.

Muscle spindles

It is estimated that we have approximately 27,500 muscle spindles, with 4000 in each arm and 7000 in each leg, and their density is the greatest in hands and neck. (Enoka, 2008) Muscle spindles continuously provide sensory feedback to the central nervous system about muscle length (stretch) by changing discharge rate of afferent primary Ia and secondary II afferent action potentials. All skeletal muscles have muscle spindles. They locate in intrafusal muscle fibers where primary Ia afferent axons ends in central area and secondary II afferent axons end in more polar areas. They are innervated by gamma motor neurons that ending also polar areas close to secondary II afferent axons (Table 3.5).

Golgi tendon organs and joint receptors

In contrast to muscle spindles, they locate in the tendons of the skeletal muscles near the muscle-tendon junction. They resemble to ruffini corpuscles in shape, they send impulses to the central nervous system via Ib afferent fibers. The Golgi tendon organs are sensitive to tension of the tendon. It functions oppositely with the action of the muscle spindle, which means activation of golgi tendon organ is maximum when the muscle spindle is inactive and minimum when the muscle spindle is active.

Joint ruffini corpuscles, joint pacinian and golgi organs continuously provide sensory information about current changes in the angle, direction, and velocity of joint movements. Despite some debate over their function, they also send signals when the muscle dangerously reaches to its maximum range of motion to prevent injuries (Abernethy et al., 2012).

Motor systems

Type of movements

Movements which are produced with the collaboration of many body systems can be classified according to their properties and initiation areas in the central nervous system. Table 3.6 illustrates this classification.

Reflex pathways

One of the prerequisites of understanding reflex pathways is to know about smallest functional unit of the nervous system.

Motor unit is the smallest functional unit of the nervous system and it can be regarded as the final output of motor commands (Konrad, 2005). A motor unit consists of one alpha motor neuron and all the extrafusal muscle fibers it innervates. The number of these muscle fibers can vary from 1 or 2 to 1000. If the number of muscle fibers innervated by a motor neuron is few, the motion produced by that muscle is more precise. In contrast to

TABLE 3.5 Locations and functions of different types of mechanoreceptors located in muscles, tendons and joints.

Name	Location	Function
Muscle Spindles	All skeletal muscles, located in intrafusal muscle fibers, primary Ia afferent axons ends in central area, secondary II afferent axons ends in more polar areas, they are innervated by gamma motor neurons that ending also polar areas close to secondary II afferent axons	They continuously provide sensory information about rate of muscle length (stretch) by changing discharge rate of afferent primary Ia and secondary II afferent action potentials, their number is high in the muscles control fine-tuned precise movements and fewer in the muscles that control gross movements
Golgi Tendon Organ	They are located in the tendons of skeletal muscles near the muscle-tendon junction, they resemble to ruffini corpuscles in shape, they send impulses to the central nervous system via Ib afferent fibers	They continuously provide sensory information about muscle tension which occurs when the muscle contract against a force (valid even at low levels of tension), they also send signals when the muscle dangerously contract to prevent injuries
Joint Receptors Joint: Pacinian Joint: Ruffini Joint: Golgi Organ	Joints capsules and ligaments that binds the joint together	They continuously provide sensory information about current changes in the angle, direction, and velocity of joint movements. they also send signals when the muscle dangerously reach to its maximum range of motion to prevent injuries

TABLE 3.6 Type of movements.

Name	Properties	Initiation	Example
Spinal Reflexes	Spinal reflexes are a rapid response against afferent sensory feedback	Spinal cord, depends on the rate of specific sensory stimulation	Blinking of the eye, patellar tendon reflex
Automatic Behaviors	They are a combination of reflex and purposeful movements	Initiation is voluntary and in high brain levels but the execution is in lower levels	Walking, running, chewing
Voluntary Movements	Purposeful and volitional movements, they can be improved with practice	Initiation entirely within the upper levels of central nervous system	Hitting a tennis ball, playing an instrument, kicking a soccer ball

this if the number of muscle fibers innervated by a motor neuron is high, the muscle produces gross movements.

The recruitment order of motor neurons depends on their size. That is, muscle fibers which are the smallest and low force production capacity are recruited first. This phenomenon is known as Henneman size principle (Henneman et al., 1965).

When afferent signals from sensory systems reach to the central nervous system, spinal cord can evoke a rapid response, which is called reflex. Reflex pathways are responsible for two main functions in human body. The first one is to protect muscle from injury in case of instant involuntary movements. The second one is to control fundamental rhythmic actions which are initiated in higher brain centers.

A reflex arch needs four main components to create a reflex response; (i) receptor (transduces mechanical, temperature or vibration stimulus into encoded electrical signals), (ii) afferent (transmits electrical signals to the central nervous system), (iii) efferent (transmits output signals from central nervous system to the effector organs), (iv) effector (creates a movement response). If only two neurons (afferent and efferent) make a synapse, it is called 'monosynaptic reflex'. When information is transmitted from afferent to efferent neurons through interneurons, it is called 'polysynaptic'. When considered %99 of all neurons are interneurons, they can modulate the transmission process between afferent and efferent neurons in all kind of movements (Enoka, 2008).

Automatic behaviors

Automatic behaviors are needed for fight or flight responses which are related with survival and postural adjustments. All the information comes from visual, somatosensory and vestibular systems are combined in the central nervous system for the execution of movements or maintenance of one part of the body in a fixed position.

Postural orientation is crucial for all movement types and directly related to automatic behaviors such as keeping head at a constant distance from a book while we are reading or maintenance of lower extremities in a stationary position. Postural orientation skills are needed also for goal-directed movements which requires the involvement of high-level brain centers.

Another important automatic behavior is balance. All the information comes from proprioceptive receptors, vestibular and visual systems informs the central nervous system about the location of the body in the space. The central nervous system compares this information to keep center of mass of the body within the base of support. In other words, the central nervous system is calibrating the space around us, which is a problematic task for the people who have bilateral vestibulopathy (Kram and Taylor, 1990).

Due to the hierarchical organization of the central nervous system, movements which require high level of cognitive and motor functions controlled by upper levels of the system (i.e., motor cortex, basal ganglia). Whereas, lower levels (i.e., brain stem, spinal cord) are responsible for the control of rhythmic and repetitive movements like walking, running.

Energetics in human movement

There are too many studies investigating the energetics of locomotion from different aspects and in comparative fashion with other mammalians and birds in the literature. Some of the studies concentrate on the energetics of human movement from; a) different aspects of movement patterns like; (i) the energetics of running, (Kram and Taylor, 1990) (ii) walking, (Gottschall and Kram, 2005) (iii) hopping (Farris and Sawicki, 2012) etc. Besides, there are some articles that are searching for scientific knowledge on the transition between run and walk (Pires et al., 2014). Moreover, some of the research groups worked on the energetics on different surfaces like energetics of human locomotion on sand (Lejeune et al., 1998). On the other hand, energy cost or energetics of different sport branches was also investigated. For example, Formenti and Minetti (2007) evaluated the evolution of ice-skating energetics through history. So, the energetics of human movement or terrestrial locomotion is a huge research area. Because of that reason, we will try to both summarize the literature related with energetics of human movement and supply basic information on energetics and its application to human movement in the current section. Besides, we will also share some basic findings about energy expenditure in bipedal and quadrupedal terrestrial locomotion in comparative fashion.

Before going into the detailed information on different aspects of energetics of terrestrial locomotion, it is decided to first supply basic information about the i) metabolic and ii) mechanical energy sources of human movement. Metabolic energy sources of human or terrestrial movement are very well established in the literature. There is a wide variety of findings starting from basic sciences to some applied sciences. However, as for the latter one, there is a variety of studies concentrating on the different aspects of the phenomena. But reaching a common conclusion is not as easy as metabolic energy sources.

Metabolic and mechanical energy sources of terrestrial movement

Human body has been described as to a multilink system powered by force actuators (muscles) (Zatsiorsky, 2002). The sport performance as like all physical exercises is the result of a coordinated activation of the appropriate skeletal muscles. These muscles, acting through the lever systems of the body skeleton, provide the forces and the power that can be transformed into skilled movements. The assessment and quantification of such physical performance is accomplished using the International System of Measurement (the SI) for *force* (newtons); *energy, work and heat* (joules); *torque* (newton-meters); and *power* (watts) (Knuttgen and Komi, 2003). Knuttgen and Komi (2003) had also suggested to define the term exercise forces generated by activating the muscles and their outcomes.

Force has been described as any interaction to change or tend to change the state of rest or motion of an object. *Work* is equivalent to a force expressed through a displacement with no limitation on time. *Torque* is defined as the effectiveness of a force to produce rotation of an object about an axis. *Power* is the rate at which work is performed or the rate of the transformation of metabolic potential energy to work and/or heat (Knuttgen and Komi, 2003).

Power is defined as the rate of energy transferred by means of a force.

$$\text{Power} = \text{Work}/\text{Time}$$

where the amount of transferred energy by the force represents the work done which is divided by the time required for that energy to be transferred by the action of the force (Campbell and Chonacky, 1975).

Two very general relationships about energetic cost of terrestrial locomotion in birds and mammals have been demonstrated by Taylor et al. (1982): "(1) metabolic power increases nearly linearly with speed over a wide range of speeds; and (2) the cost to move a gram of body mass a given distance decreases as a regular function of increasing body mass (e.g. a 30 g quail or mouse uses approximately 13 times as much energy to move each gram of its body a given distance as a 100 kg ostrich or pony)".

Energetics and mechanics of terrestrial locomotion

Assuming that skeletal muscles consume most of the energy when an animal moving across the ground, and that the muscles use this energy while generating force and performing mechanical work. Fedak et al. (1982) measured the changes in mechanical energy which take place as animals move at a constant average speed as a function of speed and body size. They aimed to quantify the rate at which mechanical work must be supplied to accelerate the limbs and other parts of the body relative to the center of mass (CoM) during each stride as an animal moves along the ground. They included a biped (ostrich) and a quadruped (horse) animal, calculated the kinetic energy of limb segments and of the entire limb plotted as a function of time for three strides. They selected the animals to have almost similar body mass (~ 100 kg) and running speed (7.5 m s^{-1}). They concluded that elastic recoil supplies a significant fraction. The increases in kinetic energy relative to the CoM when these animals run at high speeds. However, they were not very certain until they consider energy changes of the CoM. Energy exchanges are possible between the CoM and the parts of the body while a foot is in contact with the ground (Fedak et al., 1982).

Heglund et al. (1982) quantified the potential and kinetic energy changes of the CoM. They used a force platform to measure the mechanical work required to lift and accelerate small bipeds, quadrupeds and hoppers' (kangaroo rats) CoM within each step as a function of speed and body size during level, constant average speed locomotion. They concluded that small (quail) and large animals use the same pendulum-like mechanism. The animals exchanged up to 70% of the energy between kinetic and gravitational potential energy within a step. Additionally, they reported that running, trotting and hopping are also producing the similar curves of the mechanical work required as a function of time during a stride for both the small and large animals. On the other hand, a difference observed between small and large animals in galloping. The front legs are used mainly for braking, while the back legs are used to reaccelerate the CoM within a stride in small animals. The large animals use front and hind legs to both brake and reaccelerate their CoM. These significant mechanics do not allow the quadrupeds use elastic energy in their legs (Heglund et al., 1982).

While small animals showed force and velocity patterns similar to large animals during a run or hop, dogs, kangaroos and humans store elastic strain energy in the muscles and tendons during landing at high speeds. They use this energy source during take-off phase (Heglund et al., 1982).

In the final study of in a series of the publications, Heglund et al. (1982) analyzed the link between the energetics and mechanics of terrestrial locomotion. They combined the kinetic energy of the limbs and body relative to the CoM with the potential plus kinetic energy of the CoM. The main purpose was to obtain the total mechanical energy (excluding elastic energy) of an animal during a constant average-speed locomotion. They applied the equation equally as well to a chipmunk or a quail as to a horse or an ostrich, which was independent of body size. As the animal moves along the ground at a constant speed, the metabolic energy consumed by each gram of it increases linearly with speed. In summary, they found that during running at 3 m s^{-1}, quail or chipmunk consumes for each gram of tissue of a 30 g, 15 times higher than that of a 100 kg ostrich, horse or human running at the same speed while their muscles are performing work at the same rate. Their findings show that how important is the storage and recovery of elastic energy in larger animals. However, they were not able to demonstrate the exclusion of the possibility of elastic storage of energy in small animals. Their results are clear that the rate of energy consumption of animals during locomotion is not possible to define with an assumption of a constant efficiency between the mechanical work performed by the muscles and the energy consumed (Heglund et al., 1982).

They suggested that the most important factors in determining the metabolic cost of constant-speed locomotion is the intrinsic velocity of shortening of the active muscle motor units and the rate at which the muscles are turned on and off. It should be mentioned here that shortening velocity of the active muscle motor units is related to the rate of cycling of the cross bridges between actin and myosin. As animals increase speed, faster motor units are recruited. It should be noted that equivalent muscles of small animals have faster fibers than those of larger animals. Besides that, as animal increases speed the muscles are turned on and off more quickly and a small animal will be able to turn muscles on and off faster than that of a larger animal at the same speed (Heglund et al., 1982).

Comparison of bipedal and quadrupedal locomotion

Till now, we have discussed the details of metabolic and mechanical energy sources of terrestrial movement. We have approached phenomena in comparative fashion amongst running, trotting and hopping type of exercises. We think that it may be very useful to make a comparison between bipedal and quadrupedal terrestrial locomotion. In terms of energy expenditure and movement efficiency, what we -as human- have gained and what we have lost in bipedal locomotion. Therefore, this could be valuable for the readers that whether bipedal locomotion is advantageous or disadvantageous comparing with other terrestrial locomotion.

Palaeo-anthropologists have been continuing to search for the answer for the question of when, and how, hominids acquired habitual bipedal locomotion. The most prominent milestone in hominid evolution is the acquisition of habitual bipedalism and it is considered to be a hominid identifying mark. The ancestral quadrupedal gait and the newly adopted bipedal gait, each of that showing habitual locomotor mode corresponding anatomical adaptations are very different. For early hominids, all great apes (and some other primates) have been proposed as models. Chimpanzees (*Pan troglodytes*) and bonobos (*P. paniscus*) are the closest living relatives to humans and their locomotion is valuable for comparison with other primates, and to gain an insight in the acquisition of human bipedalism. As long as bonobos are habitual quadrupeds, they also engage in bipedal locomotion, both on terrestrial and in arboreal substrates (D'Aout et al., 2004).

Bipedal and quadrupedal walking kinematics and dynamics are not clearly different from each other. The leg movements are almost similar except for approximately 37° erected trunk position during bipedal locomotion. When the gait cycle analyzed, plantar pressure distributions show subtle differences between bipedal and quadrupedal locomotion apart from heel (D'Aout et al., 2004).

Walking involves an alternate transfer between gravitational-potential energy and kinetic energy within each stride (as takes place in a pendulum) in all animals (as in man). At intermediate walking speeds, this transfer is greatest at intermediate walking speeds. It is also responsible for about 70% of the total energy changes taking place within a stride. Muscles supply the rest of 30%. During running, hopping, and trotting, no kinetic-gravitational energy transfer takes place. However, another mechanism conserves the energy as elastic "bounce" of the body. Galloping animals uses combinations of these two energy-conserving mechanisms (Cavagna et al., 1977).

Cavagna and his co-authors (1977) (Cavagna et al., 1977) reach a common conclusion on running, trotting, hopping, and galloping movement patterns. They mention that during these movements; 1) the power per unit weight required to maintain the forward speed of the CoM is almost the same in all the species studied; 2) the power per unit weight required to lift the CoM is almost independent of speed; and 3) the sum of these two powers is almost a linear function of speed.

As human being during our daily routine, we are not quite aware of coordination between our arms and legs. However, there are still unknown parts of the coordinated locomotion between upper and lower extremities. Besides, it is still questioned that whether upper extremities are necessary for human locomotion. This is contradictory when we observe the cats and dogs around us that they use forelimbs and hindlimbs synchronously to produce a quadrupedal locomotion. This phenomenon explained by Zehr et al. (2009).

a. Evidence for Linkages between The Upper and Lower Limbs

It is proved in the literature that quadrupedal coordination elements between arm and leg activity are likely conserved during bipedal human locomotion. As it is not easy to obtain interlimb locomotor evidences, reflex studies can be utilized for some evidences to detect such neural activity. Frigon et al. (2004) conducted a study to search for the information to prove the interaction between the movement of the arms and legs. They have chosen rhythmic arm cycling during which they have measured H-Reflexes in leg muscles. They found that arm cycling causes a reduction in soleus H-reflex amplitude. They concluded that this suppression was mediated by changes in presynaptic inhibition of muscle afferent transmission that occur only during rhythmic movement.

b. Characteristics of the Coupling between the Forelimbs and Hindlimbs

The performed task affects the interlimb neuronal linkages in humans, and connectivity between the links increases when the task is relevant. Lamont and Zehr (2007) found that holding an earth-referenced handrail can alter cutaneous reflex amplitudes in muscles across the entire body. There are some evidences demonstrating that rhesus monkeys indicate that lumbar segment having more highly coordinated locomotor coupling than that of cervical segments. (Courtine et al., 2005) which may be similar to humans (Zehr et al., 2009).

Primates and humans demonstrate similar patterns in terms of bipedalism and the activity of upper limbs. Bipedalism can be seen amongst great apes, which may be related with collecting the fruits from the trees during which they need to stand up to till the upright position (Zehr et al., 2009). As a result of some findings in the literature on walking energetics and biomechanics for adult chimpanzees and humans supplies more support to the long-standing hypothesis that bipedalism reduces the energy cost of walking compared with our ape-like ancestors (Sockol et al., 2007).

c. Why are there Arm-to-Leg Linkages in Bipedal Humans?

The development of obligate bipedal locomotion is one of the most significant adaptations to occur within the hominin lineage. There is considerable information on that issue in the literature. Besides, there is considerable debate too. Debates cane be divided into three parts; i) likely locomotor repertoire preceded bipedalism, ii) there is the more theoretical debate over the ecological/behavioral reasons as to why bipedalism evolved, and iii) the degree to which certain hominin taxa were obligate bipeds (Harcourt-Smith and Aiello, 2004).

Gait analysis showed some obvious biomechanical and functional differences between bipedal and quadrupedal locomotion. The center of mass is relatively high and balanced on only two legs in bipedal locomotion. This makes the role of each leg critical. To produce the gait, the arms are not essential, and they can perform independent skilled hand movements. As having some differences, the neuronal connections between rhythmic arm and leg movement may be related to the biomechanics of upright locomotion. An evolution of the use of arms for quadrupedal climbing may have occurred by using the arms for offsetting interaction torques generated during upright bipedal terrestrial locomotion (Zehr et al., 2009).

Hinrichs et al. (1987) mentioned that it has already been proven that arms reduce the magnitude of the vertical oscillations of the body CoM during walking and they may reduce energy expenditure. They have also demonstrated that the vertical excursion of the CoM of the body was larger than that of the body-minus-arms (BMA), indicating that the addition of the arms actually increased the magnitude of the vertical oscillations of the body CoM rather than decreasing it as in walking. In addition, the vertical range of motion of the body CoM was found to decrease as running speed increased. Hinrichs et al. (1987) also evaluated the horizontal motion of CoM. They reached a conclusion that both in the side-to-side and forward directions, the arms tend to reduce fluctuations in the horizontal velocity of the runner, which is thought to result in a reduction in energy cost. Instead of reducing the vertical range of motion of the body CoM, the arm swing tends to increase it.

d. How Can These Linkages Be Exploited – What are the Translational Implications for Rehabilitation?

The similarities between non-human primates and humans in terms of both the organizations of the motor systems and behaviors have defined. So that non-human primates may supply a unique model for evaluating efficacy and safety of treatments for humans after neurotrauma (Courtine et al., 2007).

Mechanical and metabolic energy cost of walking and running

More specifically, determinants of the metabolic energy cost of running have been investigated intensively. There have been different hypotheses attempting to link the metabolic requirements of both walking and running (Pires et al., 2014). It was the earlier approaches that to increase the positive mechanical power; (i) accelerate the CoM, which is considered to be an external work and (ii) accelerate the limbs or internal work. However, some of the studies opposed that increase in mechanical power with speed cannot fully explain the increase in the metabolic cost of locomotion (Pires et al., 2014). Having this knowledge, Kram and Taylor (1990) proposed a new hypothesis that generating the force that determines the cost of running is the cost of supporting the body weight during running and the time course of generating the force (Kram, 2000).

Kram and Taylor (1990) raised three assumptions to explain their speed and size approach. Their first assumption was that most of the muscular force used to oppose gravity. That means the vertical force must be at least 10 times bigger than that of the horizontal force and the average vertical force must be equal to the weight of the running specimen (W_b). So, this is to relate the volume of muscle to the running speed and size of the given animal. Volume of the muscle that exerts the force can be calculated by the cross-sectional area (Kram, 2000). The findings from former studies conducted in comparative fashion. These findings summarize that the average muscle force/ground force ratio does not change with running speed, which means muscle force averaged over a stride does not vary with the speed of the run. The second assumption was that a unit of active muscle exerts the same force on the ground regardless of speed or animal size. Finally, they assumed that muscles operate similar ranges of force-velocity relationship irrespective of speed and size.

Their hypothesis states that the rate of energy consumption per newton of body weight by the muscles of running animal (E_{metab}/W_b) is proportional to the weight-specific rate of force application, W_b/t_c divided by W_b, where t_c is the time for which the foot applies force to the ground during each stride (Kram, 2000). They have created the formula below;

$$E_{metab}/W_b = c0.1/t_c \tag{3.1}$$

where c is a cost coefficient. They also propose that testing the above hypothesis by measuring E_{metab} and t_c over range of speeds and gaits in animals of different sizes.

Beside the Kram and Taylor's (1990) hypothesis, Farris and Sawicki (2012) has also investigated the almost same phenomenon. They analyzed the effects of walking and running speed on lower limb joint power during human locomotion. They found that the relative contribution to total average power by the ankle, knee and hip joints did not change with locomotion speed. However, they have observed differences in between walking and running gaits. Farris and Sawicki (2012) have done further analysis in addition to mechanical aspect by conducting metabolic energy consumption and efficiency. The results have shown an increase in net metabolic power with speed in both walking and running. Net metabolic power has been found higher in running in the 2.0 m s^{-1} speed.

In addition to his and his research group's earlier studies, Kram (2000) worked on a review article summarizing determinants of metabolic energy cost of running. He mentioned that the links between biomechanics, muscle function and metabolic energy consumption during running continue to emerge. Cost of muscle force generation and the cost of performing mechanical work would be two incorporating factors in explaining the energetics of running. He emphasizes that the relative importance of these two factors varies under different running conditions.

To summarize the earlier findings related with the energetics of terrestrial locomotion more specifically human walking and running states that muscle force needed to perform a stride is not affected by the speed of walking and/or running. Because the force applied to the ground by the running animal is equal to body weight irrespective to running speed. So, the muscle force averaged over a stride does not change with running speed (Kram, 2000). Speed has effect on the time period (t_c) in which a single foot is in contact with the ground. Running with a shorter t_c needs involving faster and less economical muscle fibers into action. In other words, force production of smaller animals having shorter t_c values is more expensive. This can be interpreted as larger animals with longer legs and step lengths will have lower transport costs.

Measurement methods of energy consumption

As being explained almost all the details of metabolic and mechanical energy sources of terrestrial movement, it is important to supply some information about measurement methods of energy expenditure. To do so, some of the key terms need to be defined.

It is necessary to be clarified that physical activity and energy expenditure are two different concepts. Physical activity can be defined as a form of energy expenditure that occurs when skeletal muscles produce movement. Total Energy Expenditure (TEE) stands for the total amount of energy expended in a day and it includes three main components as: Resting Energy Expenditure (REE), Thermic Effect of Food (TEF), and Activity Energy Expenditure (AEE) (Nelms and Sucher, 2016).

The REE is the energy used to maintain vital basic metabolic activities such as body temperature, brain activities, the heart, the lungs and it is the largest part of the TEE. It is measured when a person is fasting at rest in a thermoneutral condition. Body composition, gender, age factors directly affect the REE (Ndahimana and Kim, 2017). The REE is about 10% higher than Basal Energy Expenditure (BEE). While BEE is measured after at least 12 hours of resting and fasting, generally in the mornings when the person just awake, for the measurement of REE 2–4 hours fasting time is sufficient (Gropper and Smith, 2012).

The TEF, also named as Diet-Induced Thermogenesis (DIT) by researchers, is the energy required for the digestion, absorption, transport and metabolism, usage and storage of nutrients and excretion after food intake (Tappy, 1996; Prat-Larquemin et al., 2000; Ndahimana and Kim, 2017). Besides, some factors such as increased stimulation of autonomic nervous system (Tappy, 1996), diet palatability, hormones, physical activity, adiposity (49), especially diet composition directly affect TEF (de Jonge and Bray, 1997; Labayen and Martinez, 2002).

The thermic effect of any activity that exceeds BEE can be regarded as AEE (52). It shows a great variability between individuals depending on many factors. While it can correspond around half of the BEE in sedentary individuals, AEE can reach one to two times of the BEE in active individuals (Pinheiro Volp et al., 2011).

True measurement of energy expenditure is necessary for; i) in epidemiological studies, ii) how effective an intervention program (Welk, 2002) and iii) in clinical setting (Rolfes et al., 2014). Doubly Labeled Water (DLW) Method, Direct Colorimeters and Indirect Calorimeters are three prominent measurement methods of metabolic energy that have been widely used by the researchers as briefly described below.

Doubly labeled water (DLW) method

The DLW method utilizes two parameters that are stable isotopes of oxygen (^{18}O) and hydrogen (^{2}H) for the proper measurement of TEE. Even though DLW method is recognized as the gold standard for its high accuracy, non-invasive nature and no movement restriction during the measurement (Park et al., 2014), it requires a high-cost equipment and expertise for both measurement and analysis. Many studies carried out by using this method for different populations including elderly people (Calabro et al., 2015). pregnant women (Butte et al., 2004), and even infants (Gondolf et al., 2012).

The principle of the DWL method is, the participant intakes a dose of $^{2}H_2{}^{18}O$, balanced with the 2 isotopes with total body water (TBW) that is assumed as 60% of the total weight. Elimination of those two isotopes from the body occurs at different rates and forms. While ^{18}O leaves the body both as water and carbon dioxide (CO_2), (^{2}H) leaves the body as only water (H_2O) (45). By using the formula below the rate of CO_2 production (rCO_2) can be calculated (St-Onge et al., 2011).

$$rCO_2(\mathrm{mol/day}) = 0.4554 \times \mathrm{TBW(mol)} \times (1.007\ k_o - 1.041\ k_h)$$

where k_o: the elimination rates of ^{2}H and $k_{h:}$ the elimination rates of ^{18}O.

And with the rate of CO_2 elicited from the formula above the TEE is calculated by using the modified version of Weir's formula (St-Onge et al., 2011):

$$\mathrm{TEE}(\mathrm{kcal/day}) = 22.4 \times (3.9 \times [rCO_2/FQ] + 1.1 \times rCO_2)$$

where FQ: food quotient.

The 2-point and the multi-point approaches are the main protocols for the DLW. The 2-point protocol requires at least three specimens as a pre-dose baseline, another specimen taken just after the isotopes have balanced in the body and a last dose taken at the end of the experiment (commonly between 10 and 14 days). The multi-point protocol is more difficult to carry on since the necessity of every day specimen intake of the certain dose until the end of the experiment. In practice, the 2-point approach commonly used by researchers with some modifications decided according to the purpose of the study (IAEA, 2009).

The most common form of modified approach of 2-point protocol includes a total of five samples collection (Trabulsi et al., 2003; Tooze et al., 2007; Cooper et al., 2013). After an overnight fast, baseline urine sample needs to be collected in the morning. Immediately after baseline urine sampling, participants drink DLW concentration based on their TBW. The amount of DLW dose was determined by the body weight of the participant instead of TBW in some studies (St-Onge et al., 2011; Zhuo et al., 2013; Butte et al., 2014). After one-hour drinking DLW concentration, participants should try to empty their bladder, but this urine sample is not collected since the isotope equilibrium is not established in the body yet. Two more urine samples need to be collected 3 and 4 hours after drinking of the DLW concentration. Participants should avoid eating and drinking between 3rd and 4th hours to not to enrich urine concentration. Finally, at the last day (typically 7th, 10th, 14th days in most of the studies) of the experiment two more urine samples should be collected (IAEA, 2009). This makes totally five urine samples, but in multi-point approach more urine samples need to be collected. Considering the circadian rhythm of the participants all the samples should be collected at the same time during the experiment (Zhuo et al., 2013; Salazar et al., 2015).

The choice of the protocol depends on the investigator's preference and both methods have some advantages. Fewer sample number gives an advantage to 2-point approach providing better estimation of TEE. However, the multi-point protocol has less analytical error by means of the advantage of data averaging. Isotope-ratio mass spectrometry method is performed to analyze urine samples for both of the protocols (IAEA, 2009).

Direct calorimetry

Direct calorimetry is the most accurate way to measure metabolic rate but its use is limited due to the high cost of the system (Kaiyala and Ramsay, 2011). This method based on the measurement of the rate of heat loss from the body through respiration and sweating (Pinheiro Volp et al., 2011). An isolated and hermetically sealed chamber is needed for true measurement. This chamber provides to participants some degree of freedom during measurement. (Schutz, 1995) Even though direct calorimetry is considered a gold standard; its usage is not common because of high cost and complexity. Another disadvantage is that it requires participant confinement at least for 24 hours or more (Pinheiro Volp et al., 2011).

Four types of direct calorimeters are available;

- Isothermal direct calorimeter which also known as heat-flow or heat-conduction calorimeters. This type of calorimeters works by maintaining a temperature wall via a constant temperature fluid (commonly water in most studies) surrounding the chamber, located on the exterior side of the wall surface (Mauron et al., 2009).
- Heat sink direct calorimeters are a liquid-cooled heat exchanger. This exchanger is capable of measuring heat lost by the subject (Webster et al., 1986).
- Direct convection calorimeters are made of an insulated chamber in which the air circulation is maintained at an exact known rate. The temperature and enthalpy differences between the entering and exiting air into insulated chamber are measured by the system (Snellen et al., 1983; Levine, 2005).
- Direct differential calorimeters involve two totally identical chambers. While one of them is housing the participant, the other one is having an electric heater measures exactly the same temperature increases in both chambers (Kaiyala and Ramsay, 2011).

Indirect calorimetry

Respiratory indirect calorimetry and circulatory indirect calorimetry are the two main forms of indirect calorimeters. Respiratory indirect calorimetry relies on the measurement techniques of inspiration and expiration of O_2 and CO_2 concentrations (Leonard, 2012). Since it is noninvasive, reproducible and has an error rate less than 1%, it is widely used by the researchers. It allows the true measurement of BEE and REE, also useful for the estimation of which energy substrates is being metabolized in a specific time period. (Pinheiro Volp et al., 2011) Circulatory indirect calorimetry relies on the measurement of cardiac output via a catheter inserted into the pulmonary artery (Flancbaum et al., 1999). This method can be used when the subjects are critically ill and no other methods are possible to assess TEE (Pinheiro Volp et al., 2011).

Table 3.7 summarizes the working principle, advantages and limitations of the three main energy expenditure measurement methods briefly explained above.

Besides these methods explained above, there are many other methods such as accelerometer, heart rate monitor, pedometer, self-report methods, bioelectrical impedance analysis, heat and movement sensors, physical activities records, dietary questionnaires and predictive equations. Since those methods mainly focus on the movement and individual reports criteria, they are not directly reflecting metabolic and mechanical energy expenditure. Nevertheless, a brief explanation of each method presented below.

- ***Accelerometer:*** They are relatively expensive, suitable for both laboratory and field conditions, noninvasive and objectively measures the PA level. However, they show an inaccuracy when PA converted into energy expenditure (Crouter et al., 2006).
- ***Heart Rate Monitor:*** They have all the advantages of accelerometers and used under similar conditions. However, there is also an inaccuracy when the activity level is so light. They are also vulnerable for noise coming from common electrical devices (Sirard and Pate, 2001; Hills et al., 2014).
- ***Pedometer:*** They are non-invasive, suitable especially for walking and motives participants to increase their PA levels. However, their usage is limited to walking and no information about energy expenditure (Thorup et al., 2016).

TABLE 3.7 Advantages and limitations of different energy expenditure measurement methods.

Method	Principle	Advantages	Limitations
Doubly Labeled Water	Isotope dilution (^{18}O, ^{2}H)	High accuracy (97–99%) No confinement Not forcing participants to change their routines Possible measurement over some days or weeks	Expensive Sophisticated equipment Expert personnel No information on physical activity and substrate oxidation
Direct Calorimetry	Rate of heat loss from the body through respiration and sweating	High accuracy especially for quantifying TEE Allows some degree of freedom	Expensive Sophisticated equipment Expert personnel Requires at least 24 h subject confinement
Respiratory Indirect Calorimetry	Monitoring of O^2 consumption and CO^2 production	Very accurate (error rate $< 1\%$) Non-invasive Reproducible Gives information on substrate oxidation Allows assessment in field environment conditions	Relatively expensive Relatively complex Trained personnel needed for correct use and assessment
Circulatory Indirect Calorimetry	Measurement of cardiac output via a catheter inserted into the pulmonary artery	Useful when any other methods are impossible	Invasive Underestimates REE values

- ***Self-Report Methods:*** They are suitable for large sample size and they are low-cost too. Their accuracy and reliability is so low since the data collected depends on participant's memory (Welk, 2002).
- ***Bioelectrical Impedance Analysis:*** This is an inexpensive and non-invasive method. It can estimate the REE based on the estimation of body composition, the body fluid state distribution and intra and extracellular spaces. Many factors may influence the results such as hydration state of the participant, fasting degree, PA state, menstruation, age, ethnicity, body composition and nutritional condition (Pinheiro Volp et al., 2011).
- ***Heat and Movement Sensors:*** They are inexpensive and practical but unreliable especially for overweight and obese participants (Papazoglou et al., 2006; St-Onge et al., 2011).
- ***Physical Activity Records:*** They are extremely detailed daily activity records. Even though they are suitable for individual assessment, comparison between groups is not possible due the existing different activity codes (Ainsworth et al., 2000).
- ***Dietary Questionnaires:*** They are very simple and affordable. However, very unreliable especially when the subjects underreport their food intake. Rather than obese and overweight people, this method is suitable for the participants that are able to maintain a stable weight (Johnson et al., 1998; Bellisle, 2001).
- ***Predictive Equations:*** While they are cheap, fast and simple, they can overestimate or underestimate measurement since they mainly are based on weight and height (Weijs et al., 2008).

It is important to emphasize that there are many factors may affect the determination of TEE. Considering many measurement methods, researchers should be very careful in deciding which method is the best for the investigation, what aspects researcher wants to assess and target population characteristics.

Conclusion

As a summary, he neural control processes of reflex, autonomic and voluntary movements are extremely complex. Human nervous system collects information from the environment and inner body via receptors. This sensory information comes principally from vision and proprioception. All the information comes from receptors located in muscles, tendons, ligaments, joints, skin and also the vestibular system constitutes proprioceptive information, which is vital for execution of movement patterns. High-level brain areas modulate this huge information with existing knowledge and create appropriate motor responses. Motor units serve as a bridge between the nervous and muscular systems. Control of reflex movements and generation of some basic gross movement patterns within automatic behaviors is possible at the spinal cord level. Whereas, the involvement of the high-level brain areas is needed for planning, initiation and execution of goal-directed voluntary movements. Energetics of terrestrial locomotion is one of the scientific disciplines where to many different aspects of the topic has been investigated. The most remarkable findings of the studies are that the force production of moving animal not effected from the speed. The smaller is the animal the more energy is needed to move forward.

Mechanical energy stands for the conversation of potential energy into kinetic energy. And metabolic energy is needed for many energy requiring tasks a cell must perform such as movement, synthesis of macronutrients, digestion and excretion. Elastic energy storage and release mechanisms when tendon, muscle and other surrounding tissues are stretched, explained throughout the chapter. Moreover, comparison of bipedal and quadrupedal locomotion has been addressed based on the existing literature. Measurement methods of energy consumption varies from complex methods such as Doubly Labeled Water method to Predictive Equations which are quite simple and suitable for large sample size. Selection of the proper method directly depends on the purpose of the study considering the validity and reliability of the method.

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Chapter 4

Architecture of human joints and their movement

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Classification of joints

There are many classifications according to the nature of the joints. A joint is an articulation between two bones, include the cartilage on the bones, and they are commonly classified by functional or by structural. The structural classifications of the body joints are based on how the bones are held together and articulate with each other, and the functional classification of body joints is based on the degree of movement found at each joint (Williams, 1995; Moore et al., 2014).

Joint complexity, functional and structural classification, shapes, axes, planes, degrees of freedom, and congruency will be referred to and briefly explained in this chapter.

Joint complexity

Simple joint: It refers to the joint between articular surfaces of only two bones. Usually, one surface is convex and the other one is concave.

Compound joint: It is the type of joint that is formed between more than two bones, more than a single pair of mating articulating surfaces within a single joint capsule, like the elbow.

Complex joint: This type of joint has an interarticular inclusion within the joint cleft that interposed between the joint surfaces such as a meniscus or disc, like tibiofemoral joint (Lippert, 2011; Moore et al., 2014; Floyd, 2015).

Functional classification of joints

The functional classification of body joints is determined by the degree of movement available between the bones. There are three functional classifications of joints in the body: synarthrosis, amphiarthrosis, and diarthrosis (Lockard and Oatis, 2009; Lippert, 2011; Floyd, 2015; Sara and Neumann, 2017) (Table 4.1).

Synarthrosis type of joints provide a strong union between the articulating surfaces and has little or no movement. The sutures and the manubriosternal joint are an example of synarthrosis joints. *An* ***amphiarthrosis*** type of joint has a little mobility compare to the synarthrosis type of joints. The symphysis pubis in the pelvis, and the bodies of adjacent vertebrae example of amphiarthrosis joint. The third functional joints are the *diarthrosis* joints. This type of joints are freely mobile synovial joints and they are divided into three categories based on the number of axes of the motion. A uniaxial-diarthrosis joint, like the knee joint that allows for a motion in one plane around one axis. A biaxial-diarthrosis joint like the metacarpophalangeal joint, produce movement within two planes. And, the multiaxial-diarthrosis joints like the hip and shoulder joints, allows for multidirectional motion along three axes in all directions; anterior-posterior-medial-lateral, and rotation.

Structural classification of joints

The structural classification of joints is based on the type of tissues presenting between the articulating surfaces. There are three structural classifications of the joints in the body: ***fibrous, cartilaginous joint***, and ***synovial joints*** (Lockard and Oatis, 2009; Lippert, 2011; Floyd, 2015; Sara and Neumann, 2017) (Table 4.1).

Fibrous joint

Joint surfaces are united by fibrous connective tissue and can be further sub-classified into sutures, syndesmoses,

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TABLE 4.1 Classification of joints.

Functional	Axes	Structional	Movement	Example
Synarthrosis		**Fibrous**	Suture	Cranial sutures
			Syndesmosis	Distal tibia-fibula
			Gomophoses	Dentoalveolar joints
Amphiarthrosis		**Cartilaginous**	Synchondrosis	Epiphyseal plates
			Symphysis	Symphysis Pubis
				Intervertebral joints
Diarthrotic		**Synovial**		
	Uniaxial		Hinge-Bending motion	Elbow;
				Interphalengeal
			Pivot- Rotation	Atlanto-axial;
				Radioulnar
	Biaxial		Condyloid/Ellipsoidal	MCP; Radiocarpal
				Knee
			Saddle	I. CMC
	Multiaxial		Ball and Socket	Shoulder; Hip
	Nonaxial		Plane	Intercarpal, intertarsal
				Posterior facet joints

and gomphoses. Sutures are immovable joints (synarthrosis), in which bones are united by a collagenous sutural ligament or membrane. Sutures are only found between the flat, plate-like bones of the skull.

A syndesmosis is a fibrous joint which consists of two bones that are united by a sheet of fibrous tissue and usually allow a small amount of motion (amphiarthroses). The radioulnar joint and tibiofibular joint are examples of a syndesmosis joint. And the last fibrous joint gomphosis joint is also immovable joint, which the bones are connected by fibrous tissue. They are only found where the teeth articulate with their sockets in the maxilla or the mandible.

Cartilaginous joint

A cartilaginous joint has limited mobility, which the joint surfaces are joined by hyaline or fibrocartilage and can be further sub-classified into *synchondroses and symphyses.*

In a synchondrosis, joints are immovable (synarthrosis), connected by hyaline cartilage and permit bone growth, while also providing stability and allowing a small amount of mobility. An example of a synchondrosis is the joint between the diaphysis and epiphysis of a growing long bone. *Symphysis* joints are strong joints, where the bones are united by a layer of fibrocartilage, and slightly moveable (amphiarthrosis). They are good for shock absorption and provide structural strength.

Synovial joint

In a ***synovial joint***, the articulating surfaces are connected within a joint cavity that is filled with a lubricating fluid. These joints are freely movable (diarthrosis) and are the most common type of joints found in the body. Synovial joints, based on the shape of their articular surfaces and the movements are permitted, and can be classified into six major categories; Hinge, saddle, pivot, condyloid, plane, and ball-and-socket joints.

Hinge joint

Hinge joint; The joint surfaces have smooth surfaces, they are uniaxial, allowing motion in only one plane, one axis of rotation. Ligaments of the joint help the surfaces from sliding off from one side to the other. The humeroulnar joint and the interphalangeal joints of the fingers can be given for an example (Fig. 4.1).

Pivot joint

Pivot; These are uniaxial joints, the only movement allowed is the rotation of one bone around its own long

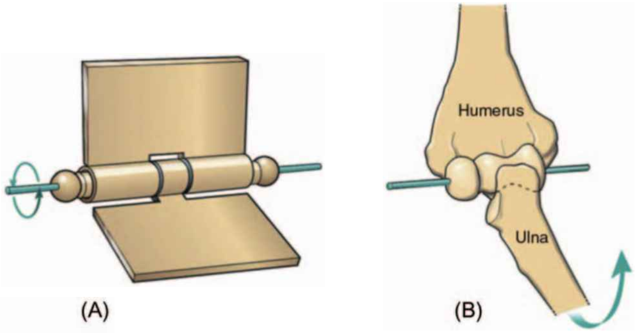


FIGURE 4.1 A hinge joint. (A) As in the hummeroulnar joint. (B) Elbow flexion- the needle shows the axis of rotation.

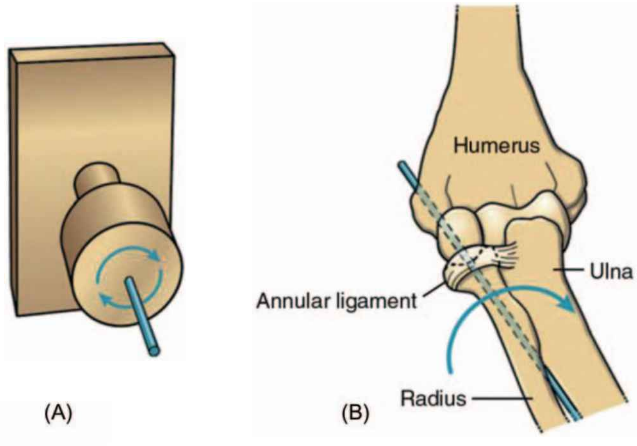


FIGURE 4.2 A pivot joint. (A) As in the proximal radioulnar joint. (B) Elbow rotation- the needle shows the axis of rotation.

axis. Examples include the proximal radioulnar joint and the atlanto-axial joint (Fig. 4.2).

Condyloid joint

Condyloid; The joint is a biaxial joint, allowing motion in two planes; flexion and extension, abduction and adduction, and circumduction. One convex surface articulates with one concave elliptical cavity. They are also known as an *ellipsoid* joint. Examples include the radiocarpal, metacarpophalangeal joint (Fig. 4.3A and B).

Saddle joint

Saddle; These joints are shaped like a saddle, and permit movement in two planes and are biaxial joints. Each side of the saddle joint has two surfaces with concave and convex portions that fit together. Examples of the saddle joints include carpometacarpal joints of the thumb, and the sternoclavicular joint (Fig. 4.4).

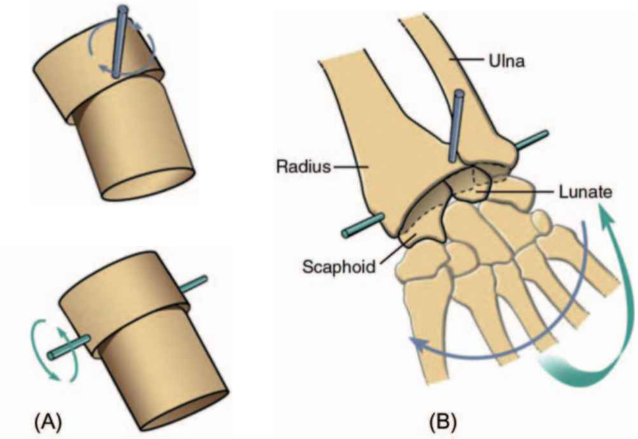


FIGURE 4.3 An ellipsoid joint. (A) As in the radiocarpal joint. (B) Wrist movements- the needle shows two axes of rotation.

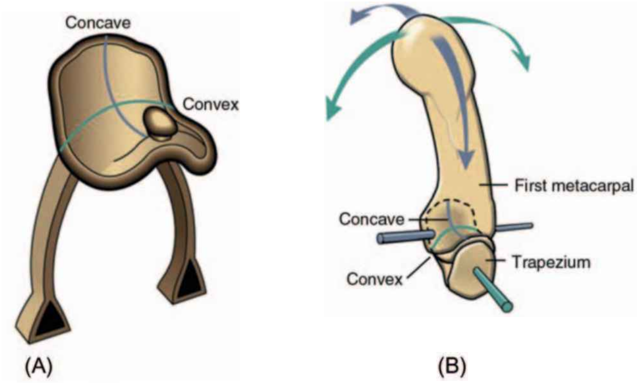


FIGURE 4.4 A saddle joint. (A) As in the carpometacarpal joints. (B) The thumb movements-two needles show two axes of rotation.

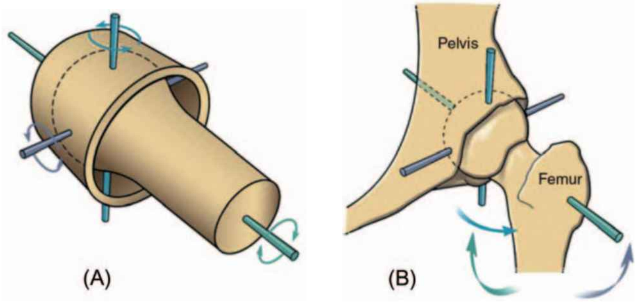


FIGURE 4.5 A ball and socket joint. (A) As in the hip joint. (B) Hip movements- needles show three axes of rotation in multiple planes.

Ball and socket joint

Ball and Socket; These joints allow the greatest range of movements in multiple planes and are called multiaxial joints. The ball-shaped surface of one bone fits into the hollow socket at the end of another bone. The glenohumeral joint and the hip joints are examples of ball and socket joints (Fig. 4.5).

Plane joint

Plane; These are uniaxial joints, allowing movement in one plane. The articular surfaces are relatively flat allowing to glide and sliding movements. Examples include the acromioclavicular joint, intercarpal and intertarsal joints (Fig. 4.6).

Synovial joints are designed primarily for human mobility and have some characteristic features like articular cartilage, joint capsule, joint cavity, and synovial fluid (Woo et al., 1994; Kaufman and An, 2008; Magee, 2008; Sophia Fox et al., 2009; Lippert, 2011) (Fig. 4.7).

Articular cartilage covers the articulating bones in synovial joints and helps to transmit loads and reduce friction. It acts like cushions absorb compression placed on the joint and thereby keep the bone ends from being crushed.

The joint cavity is enclosed by a two-layered *joint capsule*. The external layer is called the stratum fibrosum strengthens the joint so that the bones are not pulled apart. The inner layer, stratum synovium, is composed of dense fibrous tissue. Joint capsules vary considerably both in thickness and in composition. Capsules such as the one enclosing the shoulder joint are thin, loose, and redundant, therefore sacrifice stability for mobility. Other capsules such as the hip joint capsule are thick and dense and thus favor stability over mobility.

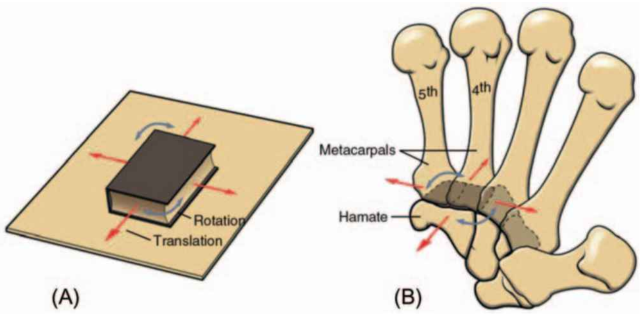


FIGURE 4.6 A plane joint. (A) A plane joint allows the bones to move in multiple movements including rotation and translation, by moving on the surface like a book. (B) As with intercarpal joints, it permits limited sliding and rotation movements between bones.

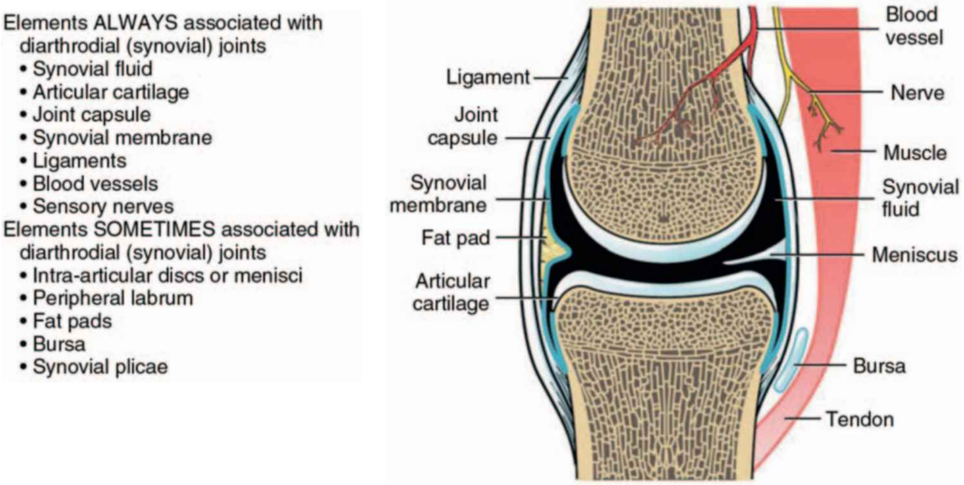
Joint cavity is a space that contains a small amount of synovial fluid. *Synovial fluid* is present in small amounts at all synovial joints that covers the surfaces of the inner layer of the articular capsule. The articular cartilage helps to keep the joint surfaces lubricated and reduces friction between the bony components. The fluid also provides nourishment for the hyaline cartilage covering the articular surfaces, as fluid moves in and out of the cartilage.

Synovial joints may be associated with accessory structures such as *disks or menisci, labrum, fat pads, ligaments and tendons* (Woo et al., 1994). Articular disks and menisci often occur between articular surfaces, making the joint more stable and minimizing wear and tear on the joint surfaces, and increase congruity. These structures are located in and around synovial joints, not only help to provide stability for the joint but also facilitate, guide and limit motion.

The stability of a synovial joint depends on mostly the shapes of the articular surfaces, the number and the positioning of ligaments, and muscle tone. Synovial joints are reinforced and strengthened by a number of ligaments. Ligaments and tendons play an important role in keeping joint surfaces together and guiding motion. Excessive separation of joint surfaces is limited by the passive stability through tension in ligaments, the fibrous joint capsule, and tendons. In addition, dynamic stability, through active tension in muscles, limits the separation of joint surfaces.

Planes of movement and axis of rotation in synovial joints

Planes of movement in the synovial joint are used to describe the structural position and directions of functional movement according to the three planes of the



Elements ALWAYS associated with diarthrodial (synovial) joints
- Synovial fluid
- Articular cartilage
- Joint capsule
- Synovial membrane
- Ligaments
- Blood vessels
- Sensory nerves

Elements SOMETIMES associated with diarthrodial (synovial) joints
- Intra-articular discs or menisci
- Peripheral labrum
- Fat pads
- Bursa
- Synovial plicae

FIGURE 4.7 A synovial joint.

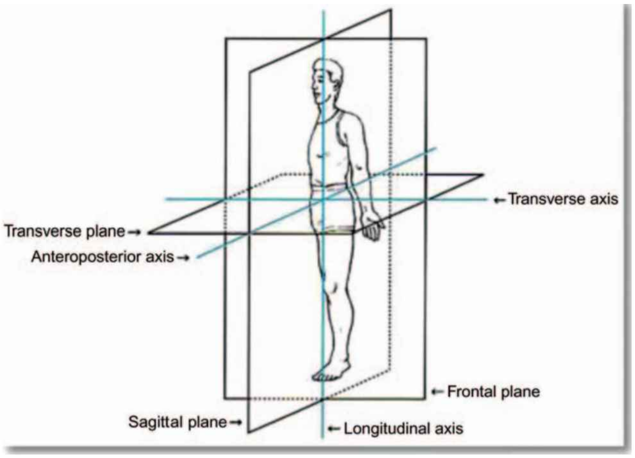


FIGURE 4.8 Movement planes and axes of rotation.

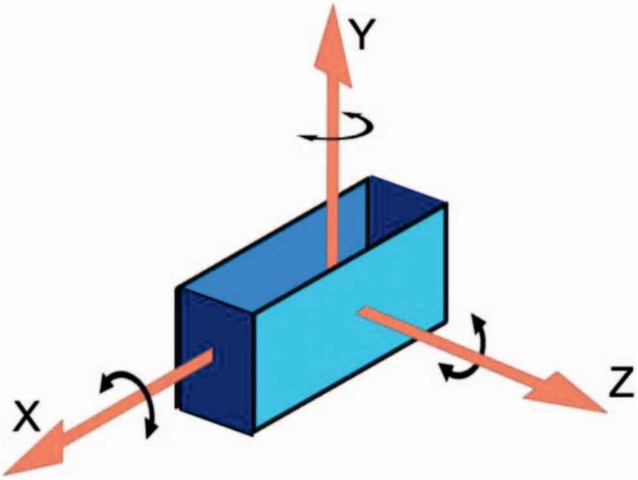


FIGURE 4.9 Degree of freedom.

body. The sagittal plane is vertical and extends from anterior to posterior, divides the body into right and left. The frontal plane is vertical and extends from side to side, and it divides the body into anterior and posterior components. The transverse plane is a horizontal plane and divides into upper and lower components (Kaufman and An, 2008) (Fig. 4.8). The movement defined as "rotation" represents the basic movements in the three planes; Flexion-extension, abduction-adduction and internal rotation-external rotation. And the axis of rotation is perpendicular (90 degrees) to the plane in which the rotation occurs. According to the classification of the joints, four types of axis may be mentioned: 1) Nonaxial, 2) Uniaxial, 3) Biaxial, 4) Multiaxial (Kaufman and An, 2008; Lippert, 2011; Floyd, 2015).

A nonaxial joint; bone movement that is not around on an axis. Gliding does not involve rotation around any axis, and gliding joints are the only examples of nonaxial plane joints. The intercarpal and intertarsal joints, and the joints between vertebral articular processes are nonaxial joints.

A uniaxial joint only allows motion in one plane and around one axis. The knee joint (hinge joint), which only allows for flexion and extension, is an example of a uniaxial joint. In addition, the joint between the atlas and axis, and the proximal radioulnar joint, which both are examples of pivot joint, are also uniaxial joints.

Biaxial joints allow motions within two planes that are flexion and extension, abduction and adduction, and circumduction. The radiocarpal joint and the metacarpal joint of the thumb are biaxial joints are resembling for condyloid and saddle joints.

A joint that allows movement in all planes and axes is called a *multiaxial joint*. In ball-and-socket joints are multiaxial joints. They allow the upper or lower limb to move in any direction. In addition, the limb can also be rotated around its long axis.

Degree of freedom

The degree of freedom (DOF) is the number of directions of movement at a joint (Lockard and Oatis, 2009; Lippert, 2011; Floyd, 2015; Sara and Neumann, 2017). It is another way of describing the motion at a joint by using the coordinate system. DOF applies to translational, as well as rotational movements. A joint in three-dimensional space has maximum six degrees of freedom; three translation motions along the x, y, and z axis and three rotation motions around the x, y, and z axis, respectively, which one can say that degrees of freedom of a joint varies from 0 to 6 (Fig. 4.9).

Synovial joint sub-classification

Even though a few joint surfaces are not exactly either convex or concave shape, most synovial joint surfaces are either convex or concave. A sub-classification of synovial joints is based on the joint shape of articulating surfaces can be categorized under two categories; saddle (sellar) and ovoid joints (Fig. 4.4) (Lockard and Oatis, 2009; Floyd, 2015; Sara and Neumann, 2017).

In a saddle joint, articulating surfaces between two bones have reciprocally curved convex and concave surfaces oriented at right angle to each other, where one of the bones forming the joint is shaped like a saddle with the other bone resting on it like a rider on a horse. Each joint surface is concave in one direction and convex in another. The articular surfaces then fit together, concave to convex surfaces. These are biaxial joints, but they allow greater freedom of movement. The bone sitting on the saddle can move in an oval shape relative to the other bone. Saddle joint provides different types of movements such as flexion, extension, circumduction and other.

The carpometacarpal joint of the thumb and sternoclavicular joint is an example of the saddle joint.

In an ovoid joint, the one articulating surface is convex, and the other one is concave. The ovoid joints allow motion in all three, two or one planes depending on the joint, where spin, roll, and slide between the surfaces is possible. Most of the joint in the body fall under the ovoid types of joint, like hip and knee joints.

Osteokinematics and arthrokinematics

Osteokinematics refers to the movement of the bones during joint motion rather than the movement of articular surfaces (Magee, 2008; Lippert, 2011; Floyd, 2015). These are the movements in the sagittal, frontal, and transverse planes that occur at joints. The normal range of motion of a joint occurs within the anatomic limits of the joint structure. The anatomic range depends on the shape structure, joint capsule, ligament, muscle, and surrounding musculotendinous and bony structure.

Arthrokinematics is the specific movements that occur at the articulating joint surfaces are referred to as arthrokinematic movement (Lippert, 2011; Floyd, 2015). These are the motions of bony segments as well as the motion of the joint surfaces in relation to another. One of the joint surfaces is relatively stable and serves as a base for the motion, whereas the other surface moves on this fixed base. When one joint surface moves relative to the other, spin, roll, slide or combinations occur. The terms rolling, spinning, and sliding is used to describe the type of motion that the moving part performs (Kaufman and An, 2008) (Fig. 4.10).

Rolling refers a series of points on one articulating surface come into contact with series of points on another articulating surface. Rolling occurs in the direction of movement. An example of rolling is femoral condyles rolling on fixed tibial plateau during flexion and extension in standing.

Spinning refers to a rotational movement around a longitudinal axis. The same point then on a moving surface creates an arc of a circle as the bone spins. An example of spinning is the radial head of the proximal humeroradial joint during supination and pronation of the forearm.

Sliding, which is a pure translatory movement, refers to gliding of one surface comes into contact with a series of points on another surface. For example, in the hand, the proximal inter phalanx slides over the fixed end of the metacarpal during flexion and extension.

Joint motions commonly include a combination of these motions. These coupled joint motions are important in order to maintain joint integrity, while less articular cartilage is necessary for a joint to allow for movement and may decrease wear on the joint. The type of motion that occurs in particular joint depends on the shape of the articulating surfaces.

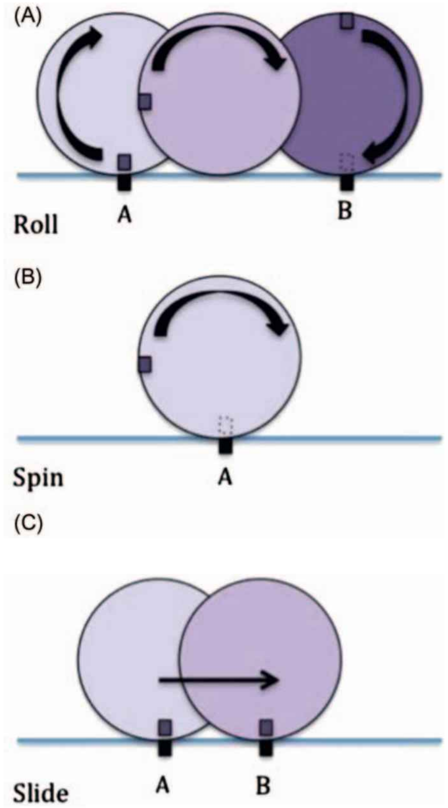


FIGURE 4.10 Type of movements (A) rolling, (B) spinning, and (C) sliding.

Most movements occur around and through several axes simultaneously. The nature and extent of the individual joint motion are determined by the joint structure and, specifically, by the shape and direction of the joint surfaces. Because of the incongruence between joint surfaces, all joint surfaces have some degree of curvature that is not constant yet changing from point to point. For articular surfaces to allow free movement in the appropriate direction the joint must have a certain amount of joint play. This joint play is an accessory movement of the joint that is essential for a normal functioning of the joint (Kaufman and An, 2008).

Convex and concave rules

Complex movements are small movements with many changing instantaneous axes of rotation. When an object moves, the axis around which the movement occurs can vary in placement from one instant to another, produce curvilinear motions, which is called the instantaneous axis of rotation (Woo et al., 1994; Kaufman and An, 2008; Magee, 2008; Sophia et al., 2009). When the articulating surfaces are equal size, a moving surface is larger than the stabilized surface, like in the glenohumeral joint the humerus surface is larger than stable glenoid, a pure motion such as rolling will result before the motion is completed. These motions help to increase the ROM available to the joint and keep opposing joint surfaces in contact with each other.

Convex and concave rules are used to describe the arthrokinematic movement that occurs in a joint without restriction. When the concave articulating surface is fixed, and the convex surface is moving, the gliding movement in the joint occurs in a direction opposite to the bone movement. Conversely, if the convex articular surface is fixed while the concave surface is mobile, the gliding occurs in the same direction as the bone movement. This is known as the *convex–concave rule* (MacConnaill and Basmajian, 1969; Barak et al., 1990; Neumann, 2012). This occurs because the convex bone surface always maintains an axis of rotation during joint motion. This allows the joint surfaces to stay in optimum contact with each other.

Some studies have pointed out mismatch in the convex–concave rule in the past. The glenohumeral joint did not follow the convex–concave rule clearly in the arm elevation. The head position of the humerus showed upward translational gliding movements during the arm elevation (Baeyens et al., 2001; Kozono et al., 2017). Convex–concave rules are still instrumental in clinical decision making regarding the restoration of restricted joint motion.

The concept of accessory joint motions, as they apply to joint congruency and the convex–concave rule, is clearly illustrated by MacConnaill's classification of accessory movements (MacConnaill and Basmajian, 1969) (Fig. 4.11).

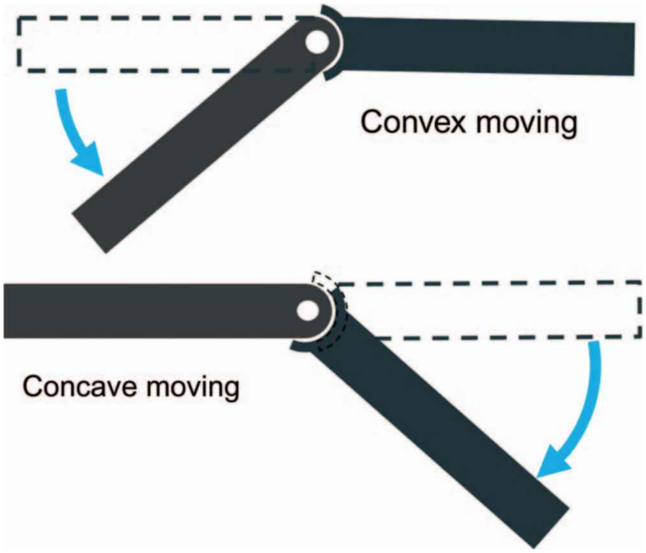


FIGURE 4.11 Convex and concave rules.

Open and closed kinematic chains

It is used to describe the kinematic concepts of body segments, especially the lower and upper extremities. The concept of kinematic chains is useful for analyzing human motion, for a therapeutic exercise, and the effects of injury and disease on the joints of the body. The kinematic chain refers to segments on the extremity that are lined up/tied together with joints (e.g.: arm/thigh, forearm/leg, hand/foot). The kinematic chain can be open or closed.

In an *open kinematic chain*, when the distal segment is free to move, or one joint can move independently of the others in the chain. Each segment of an open chain has a characteristic degree of freedom of the motion; the distal possesses a higher degree of freedom than the proximal ones. In *a closed kinematic chain*, the distal segment is fixed, and the end segments are united to form a ring or a circuit that creates a closed system. Under these conditions, movement at one joint automatically creates movement in other joints in the chain. Flexion-extension of the elbow with a weight held in the hand is an example of an open kinematic chain in the elbow joint. The push-up movement is an example of a closed kinematic chain for elbow joint (Kaufman and An, 2008; Magee, 2008; Lippert, 2011).

Joint congruency

Joint congruency is a function of the joint shape and the surrounding joint capsule, ligament structure and tension in different ranges of normal joint movement. A joint is congruent when both articulating surfaces are in contact throughout the total surface area of the joint. MacConaill and Basmajian (MacConnaill and Basmajian, 1969) have described close-packed position as the most congruent positions of a joint, where the joint articular surfaces are aligned, and the capsule and ligaments are taut and joint volume is minimal. Generally, a *close-packed position* is used for testing the capsular integrity and stability of ligaments. However, the close-packed positions are not used for mobilization techniques, because there is minimal to no joint play in this joint position. When the elbow fully extended, the ligaments and capsule are taut, allowing joint play of movement joints (Baeyens et al., 2001; Magee, 2008; Neumann, 2012)

Any position other than the close-packed position is a *loose-packed position*. This position in which the joint capsule and ligaments are most relaxed, loose, allow the maximum amount of joint play, therefore is referred to as the joints resting position (Barak et al., 1990; Neumann, 2012). The loose-packed position is ideal for testing passive mobility, applying joint mobilization techniques. Also, it is the position in which a painful, stiff, and

TABLE 4.2 Close-packed and loose packet positions.

Specific joint	Close-packed position	Loose-packed position
Glenohumeral	Abd; ER	55–70 abd; 30 horiz add, neutral rot
Radio-humeral	Flexion in supination	Full ext & sup
Humero-ulnar	Extension in supination	70 flex; 10 sup
Proc. Radioulnar	5 degrees of supination	70 flex; 35 sup
Distal Radioulnar	5 degrees of supination	10 degrees of sup
Intercarpal	Max DF	Slight flex-Ulnar deviation
Intermetacarpal	Max opposition	Midway flex & ext & abd & add
Metacarpophalangeal	1. MCP: max extension;	1. MCP: slight flex
	2–5: flight flex	2–5: max flexion
Interphalangeal	Maximal ext	PIP: 10 flex; DIP: 30 flex
Coxofemoral	Max ext, IR, Abd	30 flex; 30 abd; slight ER
Tibiofemoral	Max ext & ER	25 flex
Talocrural	Max DF	Mid inv/ever; 10 PF
Subtalar	Max invers	Midway; 10 PF
Midtarsal	Max supination	Midway; 10 PF
Tarsometatarsal	Max supination	Midway sup/pron
Metatarsophalangeal	Max ext	Neutral
Interphalangeal	Max ext	Slight flex
Vertebral	Max ext	Midway flex & ext
Sternoclavicular	Maximal elevation	Arm resting by side
Acromioclavicular	90 degrees of Abd	Arm resting by side

dysfunctional joints may move the easiest without much resistant. For example, for the humeroulnar joint, the loose-packed position is to flex the elbow at 70 degrees and slightly in supination, the intracapsular space between the humerus and ulnar joint surfaces will be increased and supporting ligaments become more relaxed. This is the resting position for this joint, and it is the best position to begin with mobilization. Table 4.2 lists closed-packed and loosed-packed positions of joints in the human body (Magee, 2008).

Joint surfaces will approximate or separate as the joint goes through a range of motion. A joint moving toward its close-packed position is undergoing compression (approximation), and a joint moving toward its open-packed position is going distraction (separation).

Congruous–incongruous relationships of joints

Knowing the shapes of joint surfaces and their congruous–incongruous relationships is the basis for pathological conditions and rehabilitation. During three basic movements (sliding, spinning, and rolling) of joints in the body, joint contact areas are constantly displaced (Bullough, 1981; Helminen et al., 1987).

In the *subtalar joint*, the congruency increases along with the load. The increase in congruency along with increased load during the push-off phase of the gait helps the windlass mechanism developed by the hyperextension of the metatarsophalangeal joint, as a result of which, the feet become more stable. In the *ankle joint*, there is a small contact area in the early stance phase of gait. In this phase, since the joint is not yet under the full body weight and as it is incongruous, the ankle goes easily to plantar flexion. In the midstance phase, however, congruency increases, and the ankle becomes more stable (Bullough, 1981; Helminen et al., 1987; Conconi et al., 2014).

In the *knee joint*, the congruous/incongruous relationship in the patellofemoral and tibiofemoral joints during knee flexion and extension is reverse (Maquet et al., 1975; Huberti and Hayes, 1984; Tummala et al., 2018).

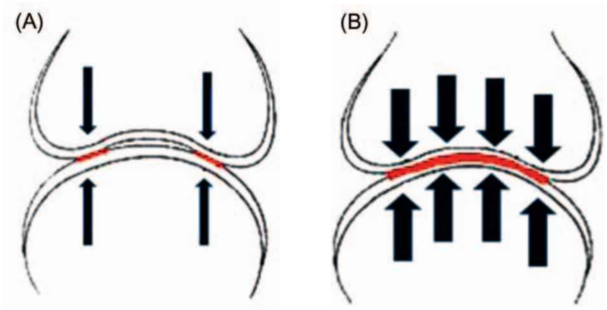


FIGURE 4.12 Contact area of joint surfaces. (A) contact becomes less when load is less. (B) As the joint load increases, the contact surface increases.

As the knee flexion progresses, the contact area increases by about 40% in the patellofemoral joint. It seems that this stability contributes to the placement of patella in the femoral sulcus and thus causes a more effective quadriceps femoris activity. In the *tibiofemoral joint*, however, the contact area of the joint is increased during extension, whereas this area is reduced by about 40% during knee flexion.

The basic load on bearing areas in the *hip joint* are the anterior and posterior sections of the lunate surface. As the load on the joint increases, the contact areas also increase (Miyanaga et al., 1984). The contact area of the central region of the lunatum is small (Fig. 4.12).

The amounts of joint the contact areas in *intervertebral articular facets* differ according to segmental level and vertebral motion (Du et al., 2016). Basically, in flexion and extension movement, while the articular contact area on both sides (left and right) decreases during flexion, it is quite the opposite during extension. In the lateral bending movement, the contact area on the side of bending is increased, while on the other side it is decreased. In addition, there are also differences in superior and inferior articular facets of the joint. For instance, in the lumbar vertebrae, the contact area of the superior facets in L3–4 and L4–5 is more than the inferior facets. In L5-S1, however, the inferior contact area is more than the superior facets. In the symmetrical extension of the movement, right-left asymmetry in the joint total contact area is observed in lumbar intervertebral joints (Jaumard et al., 2011a,b; Du et al., 2016).

In the *shoulder joint*, the joint contact area is the maximum in the functional position (half elevation position). The joint becomes more stable and support for hand functions. Joint labrum contributes to the development of about 20% of this contact area (Karduna et al., 1996).

In the *elbow joint*, the joint contact area increases with loading. The increase in loading results in the displacement of the contact areas. As the loading increases, the displacement of the contact area is towards to the lateral side of the joint. There is a minimal contact area at the radio-humeral joint when the loading in the elbow joint is in valgus direction (Stormont et al., 1985).

The amount of contact areas in the *wrist joint* does not vary much depending on the position. When the wrist is moved from flexion into extension, the contact area is displaced from the volar to the dorsal side. The highest ratio of contact area and load bearing is at the radio-scaphoid joint. The increase of the load does not cause much of a change in contact area at the wrist. Even if the load is increased, the contact area does not exceed 40% of the total joint surface area. In the wrist of *midcarpal joint*, the contact area at all joints is only 8% of the total joint surface. With loading, this area increases up to about two times. The most load-bearing joint is the scapho-capitate joint (Viegas et al., 1989).

Patho-architecture of joints

The structures forming the joint have a visco-elastic feature, which deforms under load. As the loading increases, the contact area between the joint surfaces increases and the load spreads over the articulating surfaces. Generally, the spread of the load is from the contact area to the periphery and this area expands as the load increases (Helminen et al., 1987). Along with the aging, the joint increases in the contact surfaces and congruency. This increase causes increased stability in the joint. However, in addition to the increased stability, the increase in joint friction coefficient makes mobility even more difficult. Along with this increased contact surface, it causes loading in the cartilage in areas where there used to be little or no load before. Degenerative changes arise in these areas where loading feature is low, as age-related changes are also added (Bullough, 1981, 2004; Ralphs and Benjamin, 1994; Conconi et al., 2014).

Joint congruency is shown to be different based on gender (Tummala et al., 2018). However, when the congruency of the first carpometacarpal joint is normalized to the joint size, this difference is not observed (Viegas et al., 1989). In the knee joint, congruency is found to be more in women than in men, which may increase the risk of knee osteoarthritis in women (Huberti and Hayes, 1984; Tummala et al., 2018). Nevertheless, there is no definitive evidence for the effect of joint congruency on early osteoarthritis.

The joint shape is shown to play a role in-joint fractures due to the trauma (Helminen et al., 1987; Viegas et al., 1989; Lockard and Oatis, 2009). The fractures on the concave joint surface are about 20 times more than those on the convex surface. On the convex side, fractures are mostly seen together with subluxation.

Surgical fusions in adjacent joints cause changes in the joint contact area. The fusion made in the atlanto-occipital joint is shown to cause a change in the shape of inferior of the atlas and superior of the axis in the articular surface. Surgical fusions cause an increase in a segmental rotation and result in abnormal loading in the joints. Injuries to the spinal articular facets increase spinal mobility but disrupt its biomechanical features (Jaumard et al., 2011b; Henak et al., 2013).

Diseases of joints

Under normal circumstances, the majority of the joints of the body perform without problems throughout life among most people. Joints are not indestructible; however, they are subject to various forms of diseases. Arthritis is a joint disease all of which have the symptoms of edema, inflammation, and pain. The causes are unknown, but certain types follow joint trauma or bacterial infection. Some types are genetic, and others result from hormonal or metabolic disorders. The most common forms are; *osteoarthritis and rheumatoid arthritis* (Ralphs and Benjamin, 1994; Bullough, 2004; Felson, 2013; Henak, Anderson et al., 2013).

Osteoarthritis (OA) is a degenerative joint disease that results from aging and irritation of the joints. OA is primarily characterized by progressive cartilage loss, accompanied by an increased thickness of the subchondral plate, osteophytes, and subchondral bone cysts. It is a progressive disease in which the articular cartilages gradually soften and disintegrate.

OA is associated with specific risk factors or causes including age, joint trauma, injury, joint overactivity from sports or occupation, and obesity. Genetics may also contribute to an increased risk. The aging process has an impact on the cartilage extracellular matrix structure, individuals who are over 50 years of age are at a higher risk of developing OA.

Osteoarthritis most frequently affects the knee, hip, and intervertebral joints, particularly in the weight-bearing joints (Felson, 2013; Dekker, 2015).

Rheumatoid Arthritis (RA) results from an autoimmune attack against the joint tissues. The synovial membrane thickens and becomes tender, and synovial fluid accumulates. This is generally followed by deterioration of the articular cartilage, which eventually exposes bone tissue. When bone tissue is unprotected, joint ossification produces the crippling effect of this disease. Rheumatoid arthritis tends to occur bilaterally.

Although rheumatoid arthritis is less than osteoarthritis, it is usually more damaging. Females are affected more often than males, and the disease usually begins between the ages of 30 and 50 (Firestein and Kelley, 2013).

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Part 2

Tissues

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Chapter 5

Morphogenesis and biomechanics of the human embryo and fetus

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Embryologic development

Development of muscloskeletal system

The journey of the zygote begins with the fusion of the male and female gametes (i.e. fertilization), namely the sperm and the oocyte. Activation of the oocyte after fertilization induces mitotic cleavages. After the third day of fertization, embryonic genome gets activated. As a result of this activation, compaction, blastocoel formation and blastocyst formation occurs at fourth and fifth day of fertilization. On the sixth and seventh day, hatching occurs and zona pellucida surrounding the embryo detaches enabling implantation process. Blastocyst possesses two types of cells: trophoblasts and embryoblasts. Embryoblasts form a mass of cells that is polarized at one pole of the blastocyst and this mass is termed as inner cell mass. As the implantation process proceeds, a small space appears inside the inner cell mass as the precursor of amniotic cavity. The formation of the amniotic cavity separates another type of cells (i.e. amnoblasts) from the embryoblasts. Meanwhile, morphological changes within the cells of embryoblasts cause the formation of a bilaminar germ disc. Bilaminar germ disc is composed of epiblast and hypoblast. Epiblast is the thick layer in contact with the amniotic cavity and formed of tall columnar cells. Hipoblast is in contact with the exocoelomic cavity and formed of small cubic cells (Braude et al., 1988; Carlson, 2014a,b,c; Moore et al., 2016a,b)

On the beginning of the third week, a band-like thickening, named as primitive streak, appears on the midline of the epiblast layer located at the caudal part of the embryo. The formation of the primitive streak also determines the cranio-caudal mechanism underlying the formation of the primitive streak is the proliferation of epiblast cells and their migration towards the midline of the embryo. The length of the primitive streak increases via the recruitment of cells to the caudal end. On the cranial end, the proliferation of cells causes the formation of the primitive node. The inward movement of cells in the primitive streak and primitive node towards the underlying hypoblast causes the formation of primitive groove in the primitive streak and primitive pit in the primitive node. Cells of the deep surface of the primitive node and primitive streak begin to leave the epiblast and form the mesoderm. Some cells that leave the primitive node and primitive streak displace the cells of the hypoblast and form embryonic endoderm. The remaining cells of the epiblast form the embryonic ectoderm. Thus trilaminar germ disc forms and the formation of the trilaminar germ disc is termed as gastrulation (Moore et al., 2013a,b,c,d; Carlson, 2014a,b,c).

The migration of some mesenchymal cells from the primitive node into the cranial direction forms a rodlike process, notochord, which extends between the endoderm and ectoderm to the prechordal plate (a small circular area consisting of columnar endodermal cells where the ectoderm and endoderm are fused on the cranial side of the trilaminar germ disc) in the midplane of the trilaminar germ disc. Notochord is the first structure of the future axial skeleton (Iannotti and Parker, 2013; Moore et al., 2013a,b, c,d). Paraxial mesoderm is a thickened column of mesenchymal cells that lies on both lateral sides of the neural tube (Carlson, 2014a,b,c). A compaction in the paraxial mesoderm causes the formation of spherical masses and somites on both sides of the notochord (Christ and Ordahl, 1995; Gossler and de Angelis, 1997; Kalcheim and

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Ben-Yair, 2005; Iannotti and Parker, 2013). The formation of the somites occur in a rostral to caudal direction (Kalcheim and Ben-Yair, 2005). Four occipital, 8 cervical, 12 thoracic, 5 lumbar, 5 sacral and 8–10 coccygeal somites form as a result of the segmentation in the paraxial mesoderm between the 19th and 32nd days of embryonic life (Iannotti and Parker, 2013). Somites from the second occipital to the third or fourth coccygeal persist and others regress (Iannotti and Parker, 2013). Initially somites possess and epithelial structure (Hill and Olson, 2012). A region in the somite termed as "mesenchymal sclerotome" forms as a result of an epithelial/mesenchymal transition and dissociation that occurs on the ventromedial and ventral walls of the somite (Kalcheim and Ben-Yair, 2005; Hill and Olson, 2012). The dorsal epithelial part of the somite is termed as "dermomyotome" (Kalcheim and Ben-Yair, 2005; Iannotti and Parker, 2013). Syndetome is the dorsal-most part of the sclerotome (Brent et al., 2003; Kalcheim and Ben-Yair, 2005). Meninges, vertebral column, ribs and tendons derive from the sclerotome. The dermomyotome gives rise to the cartilage of the scapula blade, dermis, endothelial cells, and vertebral and limb muscles (Christ and Ordahl, 1995; Brent et al., 2003; Kalcheim and Ben-Yair, 2005). Syndetome forms the tendons associated with trunk muscles (Brent et al., 2003). The main mass of the sclerotome, that is close to the dermomyotome is termed as "central sclerotome". The portion close to the notochord is termed as "ventral sclerotome". And the protions adjacent to the dermomyotome are termed as "dorsal sclerotome" and "lateral sclerotome" (Standring et al., 2008a,b,c). The dorsomedial and ventrolateral borders of the dermomyotome is the source of mesenchymal cells that form a separate layer; the myotome (Carlson, 2014a,b,c).

Myotomes of the somites form the skeletal muscle of the limbs and trunk (Tajbakhsh and Buckingham, 1999; Standring et al., 2008a,b,c). Each myotome has a hypaxial (ventral) division and an epaxial (dorsal) division (Moore et al., 2013a,b,c,d). Each division is innervated by the spinal nerve, which originates from the corresponding level of the spinal cord (Moore et al., 2013a,b,c,d). A fetus of eight weeks has nearly all of the skeletal muscles, which begin to differentiate from the myotomes in the fifth week of embryonic development (Iannotti and Parker, 2013). Prenatal myogenesis occurs in two phases. During the embryonic stage, the formation of primary muscle fibers is named as primary myogenesis. During the fetal stage, the development of secondary muscle fibers is named as secondary myogenesis (Yan et al., 2013). Myoblasts, mononucleated cells that differentiate from myogenic precursors, merge with each other to form syncytia, which in turn differentiates into a myotube (Iannotti and Parker, 2013; Yan et al., 2013). By the deposition of nyofilaments (actin and myosin) within the cytoplasm, each myotube differentiates into a muscle fiber (Iannotti and Parker, 2013).

Development of the cartilages begins with the proliferation and condensation of mesenchymal cells in areas termed as chondrification centers (Standring et al., 2008a, b,c; Moore et al., 2013a,b,c,d). Three types of cartilages exist in the human body: hyaline cartilage, fibrocartilage, and elastic cartilage (Moore et al., 2013a,b,c,d). For the formation of hyaline cartilage, mesenchymal cells differentiate into chondroblasts and secrete the extracellular matrix specific to the cartilage tissue (Standring et al., 2008a,b,c). Continuous deposition of the matrix separates the chondrocytes from each other (Standring et al., 2008a, b,c). For elastic cartilage formation, chondroblasts also secrete elastic fibers (Standring et al., 2008a,b,c). For fibrocartilage formation, some of the mesenchymal cell differentiate into chondroblasts and most of them differentiate into fibroblasts, which secrete type I collagen of the fibrocartilage (Standring et al., 2008a,b,c).

Bone formation occurs as two types: intramembranous and endochondral (Moore et al., 2013a,b,c,d). Intramembranous ossification begins with the condensation of the mesenchyme as a membrane (Moore et al., 2013a,b,c,d). Vasculature of the membrane increases, and some mesenchymal cells differentiate into osteoprogenitor cells, which in turn differentiate into osteoblasts and deposit osteoid (Standring et al., 2008a,b,c; Moore et al., 2013a,b,c,d). As the osteoid is laid down, it is mineralized by calcium hydroxyapatite. The deposition of the matrix around osteoblasts causes them to get trapped. These cells are further called osteocytes. The fine processes of the osteocytes remain connected with those of other osteocytes and osteoblasts (Standring et al., 2008a,b,c).

Endochondral bone formation begins with the formation of a model consisting of hyaline cartilage (Caplan, 1988; Moore et al., 2013a,b,c,d). The hyaline cartilage model is surrounded by a perichondrium, which includes osteoprogenitor cells in its' deep layers. Osteoprogenitor cells differentiate into osteoblasts, which lay down bone tissue (bony collar or periosteal bone) around the central shaft of the cartilage model (Standring et al., 2008a,b,c; Ross and Pawlina, 2011; Moore et al., 2013a,b,c,d). Nutrient deprivation within the hyaline cartilage model due to the act of the bony collar as a diffusion barrier is thought to trigger the events in endochondral ossification (Caplan, 1988; Bianco et al., 1998). As a result of nutrient deprivation, the chondrocytes in the center of the cartilage model accumulate glycogen, vacuoles occur in their cytoplasms and than they begin to enlarge (Standring et al., 2008a,b,c; Ross and Pawlina, 2011). Formation of perforated septa of thin irregular cartilage plates is the result of compression and resoprtion of the matrix between the hypertrophied chondrocytes. Synthesis and secretion of alkaline phosphatase by the chondrocytes causes the remaining cartilage matrix to calcifiy (Ross and Pawlina, 2011). The chondrocytes degenerate and enlarged lacunae remain. The lacunae get invaded by osteogenic or periosteal buds (blind-ended capillary sprouts) that arise from the periosteum (Standring et al., 2008a,b,c). Osteoclasts and osteoprogenitor cells accompany osteogenic buds (Standring et al., 2008a,b,c). Osteoprogenitor cells differentiate into osteoblasts and deposit osteoid on the residual septa of calcified cartilage. A continuous lining of bone tissue covers the cartilage residue (Standring et al., 2008a,b,c). Trabeculae form by the thickening of previously formed spicules. As these spicules includes cores of cartilage, they are termed as mixed spicules (Ross and Pawlina, 2011). The action of osteoclasts enables remodeling of the bone tissue and removal of cartilage residues (Standring et al., 2008a,b,c; Ross and Pawlina, 2011; Kierszenbaum and Tres, 2012). The long bones develop by endochondral ossification. The clavicle, which develops by intramembranous ossification is an exception (Iannotti and Parker, 2013).

Development of the joints begin with the condensation of mesenchymal cells between the neighboring developing bones (interzonal mesenchyme) during the sixth week of development (Moore et al., 2013a,b,c,d). The faith of the interzone depends on the type of the joint. It is converted into collagen, hyaline cartilage or fibrocartilage for the formation of fibrous joints, synchondroses or symphyses, respectively (Standring et al., 2008a,b,c).

The vertebral centrums begin to develop as cartilaginous models formed by the chondrogenic differentiation of cells originating from the ventral sclerotome (Standring et al., 2008a,b,c). Annulus fibrosus of the intervertebral discs are formed by the mesenchyme inside the sclerotomic fissure (Standring et al., 2008a,b,c; Iannotti and Parker, 2013). Notochord forms the nucleus pulposus, which exists in the center of the developing intervertebral disc (Iannotti and Parker, 2013). While the proximal ribs, the ventral parts and the pedicles of the neural arches and are formed by the central sclerotome, the neural arches are formed by the dorsal sclerotomal cells (Standring et al., 2008a,b,c). The source of the epaxial muscles (dorsal trunk muscles) is the dorsomedial lip of the dermomyotome. The source of the hypaxial muscles (ventrolateral trunk muscles) is the ventrolateral edge of the dermomyotome (Standring et al., 2008a,b,c).

The human extremity development is conducted with a craniocaudal and proximodistal order. The sclerotomes that will mainly differentiate into the vertebral column; make different cell clusters named as dermatomes and the myotomes. The dermatomes will make the dermis of the skin. Extremity muscles originate from lower 5 cervical and the first thoracic myotomes. The second to fifth lumbar and the upper 3 sacral myotomes, also participate at week 4 (Standring et al., 2008a,b,c; Iannotti and Parker, 2013). The extremity development occurs as a result of the critical inductive interaction between the surface ectoderm and the underlying mesoderm. Inductive interaction ends with the formation of a localized cell proliferation thait is called as the apical ectodermal ridge. The apical ectodermal ridge induces the proliferation of the underlying mesenchymal tissue. Thus the limb buds develop and elongate with further cell proliferation. The zone of polarizing activity is a mesenchymal cell aggrerate at the posterior margin of the limb bud; and it regulates the position of the limbs and the digits that will make the fingers. Limb buds possess condensed mesenchymal tissue as a core. The core is covered by the periderm, which will later make the epidermis of the skin. The dermis then underlies the epidermis. Thus the zone of polarizing activity identifies normal patterning of the extremities along the anteroposterior axis (Standring et al., 2008a,b,c; Moore et al., 2013a,b,c,d). Myotome cells from the adjacent somites are the origins of the limb bud skeletal muscles (Iannotti and Parker, 2013). The ectodermal cells and the ectodermal but neural crest origined cells make the nerves of the limbs (Moore et al., 2013a,b,c,d). The formation of specific phalangeal segments occurs by the establishment of a single cartilage model for each digit. The digit is then segmented (Carlson, 2014a,b,c). Apoptosis (the programmed cell death) within the loose mesenchymal tissue between the digital rays provide the separation of the digits and the formation of the fingers (Moore et al., 2013a,b,c,d). The tendons guide the nerves and the muscles during the development. The upper and lower limbs rotate differently and take their final positions. Bones of the limbs develop by endochondral ossification; through the formation of primary and secondary ossification centers (Standring et al., 2008a,b,c). The hyaline cartilage is first formed by chondrocytes and their matrix; then the cartilage plates disappear and are replaced by osteoprogenitor cells that will make osteoblasts. The osteoblasts secrete extracellular matrix of bone. The matrix is calcified and the osteocytes become located inside their lacunae. The cytoplasmic projections of the osteocytes make gap junctions inside their canallicules. The gap juncitons act as mechanical synapses translating all biomechanical forces between the osteocytes. Bone is actively remodeled and it can regenerate itself as it is subjected to correct biomechanical forces and hormonal stimuli.

Molecular mechanisms of muscloskeletal development

Molecular biology studies provide insight into the underlying mechanisms of embryonic development, which occurs in normal or abnormal form. It is not possible to recognize embryonic development without knowing the basic morphological and molecular aspects of embryology. In this section, the most known and studied molecules for embryonic development will be briefly mentioned. The embryonic development is guided by the significant molecules which can be divided into the following categories: transcription factors, proteins and signaling molecules between cells that have domains which have to capability to bind the DNA of the enhancer or promoter regions from the specific genes. Signal molecules are separated from the cells that produce them and perform their tasks. Many signaling molecules, termed growth factors, are units of large families of related proteins. In order to demonstrate its effects, signal molecules are ligated to specific receptors. Thus, the signal is transmitted to the cell nucleus through a series of pathways, and the events begin in sequence. Generic names are written in italics, and gene products are in the roman type, abbreviations for human genes are in capital letters (eg. HOX), and for other species just the first letter is capitalized (eg. Hox).

Transcription factors

Homeobox containing genes and the homeodomain proteins

Homeodomain proteins are the transcription factors that have critical importance on the formation of the body axe and the development of the axial and appendicular skleletal system. The homeodomain proteins include a highly conserved homeo-domain of 60 amino acids in the helical loop-coil structure. The entire 180 nucleotides encoding the homeodomain are named homeobox (Bianco et al., 1998; Kierszenbaum and Tres, 2012).

Hox Genes. At least 39 homologous homeobox genes exist in humans and the mice. Those genes are entitled as Hox genes in vertebrates and as HOX genes in humans. They are located in four clusters on four distinctive chromosomes. The Hox genes three dimensional expression pattern affects the cranio-caudal segmentation of the embryonic body in the vertebrates including human. The correct expression pattern results with the appropriate segmantalisation of vertebral column and the formation of the correct limb pattern from cranial to caudal, and proximal to distal directions. Thus different mutations on Hox genes cause skleletal dysplastic syndromes. (Tickle, 2015). Generally, the loss-of-function mutations cause the anterior posterior transformations. On the other hand, the gain-of-function mutations produce anterior-posterior organizational transformations.

Despite the Hox genes are initially informed as responsible for the main trunk axis, they function in different organs or regions such as internal-external genital regions, intestines, extremities. It also has roles in blood cells, hair follicles and development of the sperm cells. Hox genes' main function is to play a role in the regulation of structures along the main trunk axis, but they also become extrinsic in directing the development of a few specific non-axial structures (Bianco et al., 1998; Moore et al., 2013a,b,c,d).

Pax Genes. The family of Pax gene containing the nine elements characterized by a conserved DNA binding motif, and all of the Pax proteins include a paired 128 amino acid regions linked to DNA. Pax genes have a crucial role in sensory organs in embryo development and cellular differentiation processes in the nervous system and epithelial mesenchymal transition. (Blake and Ziman, 2014; Carlson, 2014a,b,c).

POU Genes. POU family member transcription factors are products of the Pit-1, Oct-1 and Oct-2 mammalian genes. In addition to a homeobox, the genes of the POU family include a region encoding 75 amino acids, which is linked to the DNA by a helical-loop-helix structure [26]. In particular, Oct-4 has a significant effect during the early division of the embryo. Oct-4 also has a significant association with the induction of totipotency and pluripotency during embryonic development (Blake and Ziman, 2014).

Lim proteins are involved in a small group of homeodomain transcription factors. Lots of the proteins have LIM domains, and these proteins have various regulatory roles in the cellular activities such as gene expression, cell migration, cell adhesion, and signal transduction of mammalian embryos (Fei and Chen, 2010). When the Lim proteins are absent, it causes the development of brainless embryos in mammals.

The Dlx gene family of the vertebrates includes the homeoboxes containing transcription factors found in pairs on the same chromosomes as the Hox genes, and these are conserved genes (Soderberg et al., 2009). Dlx gene products play an important role in craniofacial and brain structures in early embryogenesis, and in axonal and appendicular skeleton, especially in developing structures (Wu et al., 2016).

The Msx genes constitute a family of genes containing highly conserved homeobox with only two members in humans. These genes are expressed during embryonic development of the vertebrates, in multiple regions of tissue-tissue interactions. Inducing interactions mediated by the Msx genes are particularly important in epithelial-mesenchymal interactions in the face and extremities. They also play a role in physiological craniofacial, extremity, and ectodermal tissue/organ morphogenesis (Carlson, 2014a,b,c). Msx proteins commonly serve as inhibitors of cell differentiation, preserving the proliferative potential of cells in postnatal life.

T-box gene family

The genes of the T-box (Tbx) gene family show importance in developmental issues such as the induction of the mesodermal germ layer and the development of a developing limb arm and/or leg selection (Wang and Wynshaw-Boris, 2004; Wu et al., 2010).

Helix loop helix transcription factors

Basic Helix Loop Helix Proteins. These proteins carried short amino acids that are split by an amino acid sequence of the two α-helices. The basic Helix-Loop-Helix (bHLH) family has some important transcription factors, which play an essential role in the proliferation-differentiation of the cells and cell fate identification (Mahmoud et al., 2013). These proteins are very important for the development of muscle, heart, hematopoietic system, central nervous system, and many other systems (Myers and Elad, 2017).

Forkhead Gene Family. Another major transcription factor is forkhead (Fox) genes that are family members. Fox genes are expressed in various organs that develop in the body. In a developing organism, they become extrinsic in different areas and, together with other genes, direct morphogenesis of the structure (Verbruggen et al., 2016, 2018).

Zinc finger transcription factors

Sox Genes make a wide group with more than 20 members. Those molecules carry a common high mobility group, that is abbreviated as HMG domain. Sox proteins mediate several developmental processes including cardiac organ development by acting via several transcription factors (Carlson, 2014a,b,c; Vedula et al., 2017).

WT1. An isolated promoter, Wilms tumor suppressor gene (WT1) has an important function in the formation of both kidney and gonad in prenatal life (Carlson, 2014a,b,c).

Signaling molecules

A diversity of signaling molecular pathways regulate embryogenetic, organogenetic and the morphogenetic mechanisms during human development. Those patways also act after birth with some modifications. The signaling molecules provide amplified receptor mediated intracellular specific effects of the ligands. Thus the signaling family consists of a ligand (signaling molecule), Its receptor or receptors and, the signal transduction pathway effector molecules. In this section, the main signal molecules being active in morphonesis are discussed

Transforming growth factor-b family

The transforming growth factor (TGF)-β superfamily comprises of several growth factors and associated molecules modulatind different steps of embryonic development and organogenesis. Here we briefly list those molecules;

TGF-βs; Mesodermal induction, myoblast proliferation, fibronectin synthesis,
Activin; Mesodermal induction
Inhibin; Embryonic gonadal development
BMPs; Induction of neural plate, skeletal differentiation, and the other inductions
Nodal; Formation of mesoderm and primitive streak, left-right axial fixation
Lefty; Determination of body asymmetry (Soderberg et al., 2009; Fei and Chen, 2010; Wu et al., 2016)

Fibroblast growth factor family

Fibroblast growth factor (FGF) was firstly defined as a substance that induced the growth of fibroblast in vitro cell culture, in 1974. Several members of the FGF family modulates developmental processes, including branching morphogenesis, brain patterning, and limb development in the embryonic development phases and also in the postnatal body affect many function, such as the stimulation of vascular growth (Wu et al., 2016). After the secretion, FGFs are intimately ally with the extracellular matrix (Carlson, 2014a,b,c).

Hedgehog family

The hedgehog signaling molecules are among the most crucial signaling molecules known in the development of vertebrate embryos. Related to the segment-polarity molecule, hedgehog, in Drosophila, the 3 mammalian hedgehogs have been given the names of sonic, desert and indian (Carlson, 2014a,b,c).

Sonic hedgehog (shh) is a highly-conserved protein. SHH pathway is limited active in undifferentiated embryonic cells and activation of SHH signaling does not provide human embryonic cell pluripotency and proliferation (Wu et al., 2010; Carlson, 2014a,b,c). However, SHH signaling is highly activated during differentiation and influences the identification cell fate of early differentiated embryonic cells especially toward the neuroectodermal lineage (Wu et al., 2010).

Wnt family

Genes in Wnt signaling is highly preserved in eukaryotes. It is essential for development in that it modulates a various process such as cell proliferation, cell polarity, cell fate, cell differentiation, and cell migration in various vertebrates. Also during the period of gastrulation, Wnts play many important roles (Wang and Wynshaw-Boris, 2004).

Receptor molecules

Intercellular signaling molecules interact with receptors on the cell surface and act on target cells. However, for lipid-soluble molecules like retinoids, thyroid hormone, and steroids they are cell-mediated (Ross and Pawlina, 2011; Moore et al., 2013a,b,c,d; Carlson, 2014a,b,c).

Biomechanics of human uterus, embryo and fetus

Mechanical features

The embryo/fetus obliges the presence of special strategies for measuring its mechanical properties since it is extremely small and gentle. The zygote reflects physical properties of both maternal and paternal cells after fertilization. Following the formation of zygote, mitotic cell divisions endure and a strict cell to cell adhesion cause compaction of the zygote next to morula formation. Compaction continues with the formation of the blastocyst as result of shortage of adherence behavior of some cells. The embryonic cellular mechanical inreactions are followed by the formation of three germ layers, folding and the compartmantalisation of the embryo. Naming the conceptus as fetaus from week 8 follows embryonic growth. Fetus starts active body movements and respiratory activities. The first fetal movement observed in humans is a twist on head and neck at week 10. The regular body movements, breathing, leg and stretching movements appear after 15 weeks. The mother feels those movements usually between 16 and 18 an unexpected increase or decrease in fetal movements may designate fetal distress which is an obstetric emergency (Verbruggen et al., 2016, 2018).

Different forces cause linear or nonlinear deformation of the embryonic or fetal structures. The stiffness signifies a form' elastic response to a force. The modulus represents the elastic response of a sole material. Mechanical features of the embryonic and fetal tissues mainly depend on the interactions of their cellular and extracellular matrix components. Those adhesive interactions play significant roles on the way an embryo reacts to internal or external forces. In this context, the embryo can be considered as a complex material manufactured from numerous smaller composite masses of different materials. On the other hand, the time-dependant dynamic developmental processes determine the hierarchy of the mechanical measurement.

The uterus expands the volume and accommodates the growing fetus. Cervix forms the entering portion of uterus and permits uterine growth at the as an edge and should maintain its capability until it matures. Thus, the cervix has two reverse roles: to maintain the stay of the fetus during pregnancy and admit the fetus to pass during the delivery. For a successful delivery, the cervix needs 10 cm of widening. Thus, cervix undergoes histological, and mechanical changes in the second and third trimesters. The integrity of the cervix may disrupt with the loss of l stiffness that is also named as cervical incompetence. Maternal uterine contractions may increase tension load of the cervix. On the other hand, volume variations may surge the pressure. Those factors may independently or collaboratively cause preterm births (Mahmoud et al., 2013; Myers and Elad, 2017).

Measuring mechanical features of the embryo and fetus

Data on mechanical properties of embrios are mostly of ovine and animal studies (Shawky and Davidson, 2015). More recently computational methods have been used (Vedula et al., 2017). Computational methods can simulate organs alone and/or the embryo as a whole that gives access to indirect mechanical data as long as the stifnessess of tissues are well known. A limitation of computational mechanics is the obtainment of initial data by computerized tomography or magnetic resonance. The former assesses the hard tissues precisely whereas the later informs us on soft tissues. Limitations of computerized tomography are radiation and borders of most tissues cannot be precisely measured in a regular magnetic resonance imaging. One other method is the use of ultrasound recently. We have been recently using Shear Wave Ultrasonography to assess stiffness and elasticity of tissues in humans (Tas et al., 2017a,b) that can easily be adapted to measuring embryonic tissues in vivo and/or in situ. Ex vivo experimental measurements of the complex mechanical properties of embryos require perturbation of tissues while observing deformations using force transducers and mechanical or optical displacement recorders. Once stiffness measurements are completed, theoretical and/or mathematical models can be developed. Measuring embryonic tissue stiffnesses with a micro-indentation probe under the microscope requires a model for the contact between the indenter and the tissue. The Hertzian model that is commonly used requires repeated measures for validation (Lin et al., 2007a,b). Such a method may have numerical errors and usually relies on estimations that limit the development of more sophisticated models including finite element modeling (Zamir and Taber, 2004a,b). These methods can however inform us on how mechanical properties of tissues aid development and folding of the embryo in time.

Laser scanning confocal microscopy combined with laser ablation is another advanced method for assessing mechanical properties of embryonic tissues (He et al., 2014). This technology allows recording mechanical information at the tissue and cell scale before and after the tissue is stressed. If electrical or magnetic field forces are applied tissues and cells may deform however incorporating iron nano particles into cells may allow them to move in a direction (Tasci et al., 2009). Repeatability of magnetic-field application to cells using nano-iron particle incorporation needs to be assessed.

Scale of forces that can be applied to embryonic and fetal tissues needs to be at nano levels. Precision of instruements exegerating force on embryonic tissues is of critical importance and may alter results (von Dassow and Davidson, 2007). Indentation of embryonic tissues at nano-scale applies compression and tension forces however rotational sheer forces cannot be evaluated. Mechanical testing machines are used to apply direct tension and compression forces on tissues. If hard tissues should be examined, we can also apply three or four-point bending. While applying tension, grip is important (Benko and Brodland, 2007; Davidson et al., 2009). We frequently experience that the soft tissues of embryo easily loose from sutures so care should be given from where the structure disrupts. The activities of the embryo and then those of the fetus, consist of head, jaw, neck extremity and whole body movements. The respiratory movements continue during entire gestation. The main imperative biomechanical commands in the dynamically controlled physical environment are the ability of fetus to move freely and the developmental conditions in which reduced or abnormal fetal movements occur (Nowlan, 2015).

Biomechanical forces are natural parts of normal bone and joint formation (Verbruggen, 2016) as assessed in three 20–22 weeks-old fetuses by computational methods obtained from cine-magnetic resonance (MR) data. The average uterus deflection and reaction force generated by a kick was measured as 6.95 ± 0.41 mm and 0.52 ± 0.15 N, respectively in that study. Predicted maximum force in the muscles surrounding the hip and knee joints were approximately 8 N and 21 N, respectively. Biomechanical coupling facilitates spinal neural tube closure in mouse embryos zippering by supracellular F-actin network (Galea et al., 2017). Polarized cell interalation extend development in the anterior-posterior direction during early gastrulation. The embryo is shaped by active and viscoelastic properties. Mechanical forces may vary in temporal and spatial tissue stiffness. This is mostly observed in para-axial mesoderm but not the notochord level. Cells of the embryo but not the extracellular matrix are under the influence of such mechanical forces. Actin and myosin II contractility further determines mechanics at the subcellular level. Microtubules control tissue stiffness by regulating the actomyosin network through a Rho-GEF mediated signaling pathway.

Joint cartilage development and differentiation is under the stem cell lineage commitement (Responte et al., 2012). Mechanical forces control progenitor cell migration, maturation and maintenance of cartilage homeostasis (Responte et al., 2012). If an embryo is considered as being built from cells that are assembled into tissues than mechanical forces such as vectors, magnitude and location of applied force can be assessed alone and/or in combination. The embryo or its components can be considered as viscoelastic structures. When forces exceed a critical level than embryo structures may fold, bend, role or disappear. Germ layers, cells, their walls and the extracellular matrix build up the embryo into a non-linear geometry. Deformation, strain and flow cause kinematic changes in the embryo (Davidson, 2011). Changes of forces and stress of tissues can be measured and modulus can be calculated. Microsurgically isolated embryonic tissues can be tested by tension or compression however limited size of tissue sample is a common problem. Compression experiments in fetal and embryonic tissues are challenging. Microaspiration and indentation on tissues provides valuable mechanical information. One other approach is assessing tissue deformation after centrifugation. Analyzing the shape after centrifugation and working on embryo microrheology using atomic force microscopes are established for embryo and fetus mechanical studies in animals (Davidson, 2011). However, less is known on human embryo and fetus biomechanics. Laser ablation of the animal embryo allows investigation of epithelial sheets and their functions. Recently a study (Adamo et al., 2009) revealed that biomechanical forces promote embryonic haematopoiesis during the development of the cardiovascular sytem. Fluid-sheer stress increases Runx1 in CD41 + cKit + haematopoietic progenitor cells.

This chapter includes the mechanical forces on the human embryo and fetus and focuses on biomechanical forces generated by the fetus itself.

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Chapter 6

Architecture of bone tissue and its adaptation to pathological conditions

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Introduction

Bone that forms the skeleton and the basic structure of our body has several functions including mechanical support, mineral storage, blood cell production and protecting internal organs such as the brain, the spinal cord, the lungs and the heart. Bone is also the main source of mesenchymal stem cells (MSC) of the body. Rigid structure of bone provides attachment sites for skeletal muscles that aid movement. At the same time its elasticity prevents bones from fractures. Shape of bones that are defined as flat, long, short and irregular also determine their function and activity. The dimension of the long bones is greater, and they have a shaft that is called the diaphysis and two ends named as epiphysis. The broader part of the bone between the epiphysis and diaphysis is known as the metaphysis and the large cavity full of bone marrow is called as the medullary cavity. The diameter and length of the short bones are almost equal. They usually create movable joints for other neighboring bones such as in the wrist and ankle-foot. Flat bones are relatively thick due to having two layers. Irregular bones do not have any regular shape fitting to other groups. The vertebra is a good example to irregular bones. Bones longitudinally grow by their physis. This is of cartilage cells and matures after adolescence. Broadening of bone is through apophysis. Bone has a regeneration capacity of its extracellular organic and inorganic matrix through its of cells named as osteoclast, osteoblast and osteocyte.

Macroscopic Bone Types

Mature bone can be classified according to its density and density zones. Bone, therefore, exists in two forms:

Cortical (Compact) Bone

Cortical bone is a connective tissue organized as regular layers or sheets of tissue named as lamellae. Thickness and form of lamella may change from bone to bone and the location of the bone. Weight bearing bones such as the femur has more lamellae and they are thicker compared to less load-bearing upper extremity bones. In a transverse section, these lamellae are thicker in load-bearing sites. For example, in the human femur, lamellae are thicker in the medial and frontal when compared to the lateral and posterior cortex. Collagen fibers in lamellae are also organized regularly. They are in circular form and resist very well to physiological loads. Cortical bone tissue is mostly located in the outer layer of the long bones forming the shaft and inner part of the trabecular bone at the proximal and distal ends of the bone tissue. Moreover, it constitutes about 80% of the total mass of the skeleton in our body. The periosteum covers all bones.

Trabecular (Spongy) Bone

Trabecular bone is a connective tissue in which lamellae therefore collagen fibers are irregularly arranged. Trabeculae containing lamellae interconnect each other in order to form a trabecular tissue mesh. Trabecular bone is located within metaphysis, epiphysis, and medullary cavity at the end of long bones, and in short bones as well. Metabolic activity such as bone cell production and mineral exchange is higher in trabecular bone compared to cortical bone.

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Microstructure of the Bone

Mature or secondary bone constitutively comprises regular or irregular lamellae and Haversian systems or trabecular systems. The organic extracellular matrix (ECM), which is mainly of type I collagen, water and hydroxyapatite (HA) form the microstructure of cortical and trabecular bone. Different type of bones can be characterized by the composition of collagen fibers and minerals. In the ECM, collagen fibers form lamellae by aligning in parallel and creating spiral forms. Nano HA crystals gather between the collagen fibers and provide strength and rigid structure of the tissue (Wang et al., 2010a,b,c).

Bone architecture

Mature bone (compact and spongy)

Compact bone is located near the periosteal surface on the outer shell of all bones and contains a regular canal system. The Haversian systems, i.e. osteons, are placed in parallel along the long axis of the bone (Fig. 6.1). Each osteon refers to a cylindrical unit in which small blood vessels, nerves, loose connective tissue and resting osteoprogenitor cells. It is defined as the smallest functional unit of bone. Haversian canals also connect with the marrow. Osteocytes reside circumferentially in the spaces called lacunae (osteoplast) and only one osteocyte rests in each lacuna (Fig. 6.2). Remnants occur because of the resorption of the osteons by osteoclasts during the remodeling of the bone. These remnants are called interstitial lamellae, which are found between the concentric lamellae. In addition, Volkmann canals are positioned vertically to the long axis of bone in order to interconnect Haversian canals (Fig. 6.3). The incoming blood first passes through the periosteum, foramen nutricium – located on the outer shell of the bone –, and then Volkmann canals and Haversian canals. Blood circulation of bone is therefore high and very well organized. In mature bones, at the sites where tendons and ligaments are attached, collagen fibers form 'Sharpey fibers' in order to build a strong transition zone between bone and tendon.

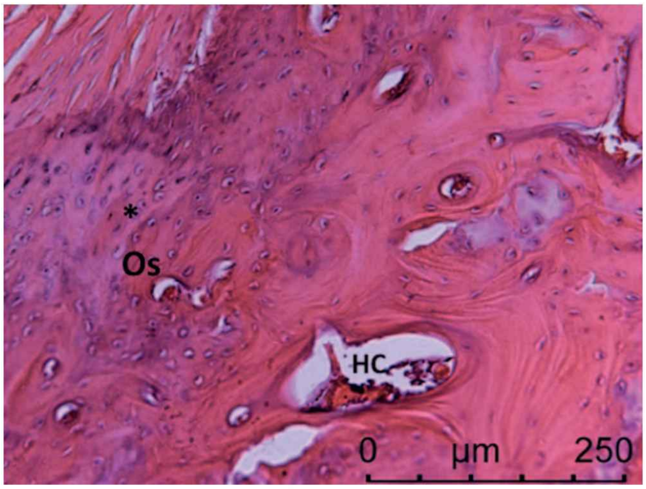

FIGURE 6.1 Compact bone; composed by Haversian canals (HC) and osteocytes (*Os) are shown (200x, Haematoxylin Eosin).

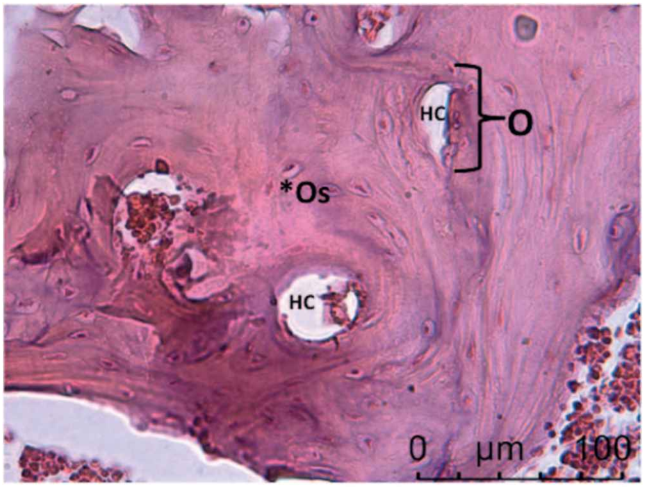

FIGURE 6.2 Haversian canal, including osteocytes (Os), osteoblasts (Ob) and endothelial cells (En) are shown (1000x, Haematoxylin Eosin).

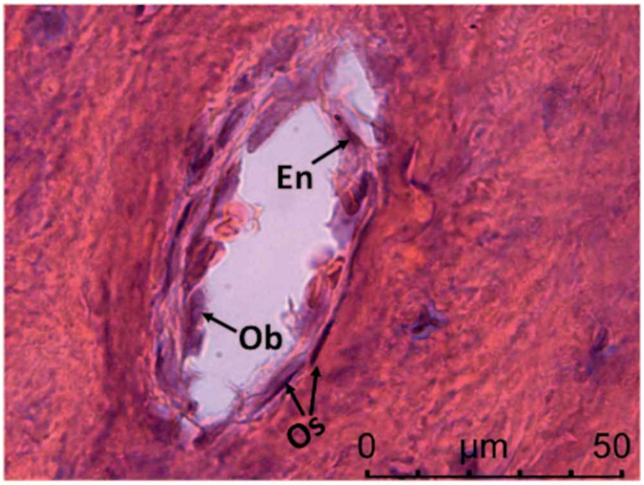

FIGURE 6.3 Compact bone and Haversian canals (HC) are demonstrated in the micrograph. Note that representative osteons with osteocytes (O), Haversian canal (HC) and lamellae are also observed (400x, Haematoxylin Eosin).

Trabecular or spongy bones are found in the inner parts of the epiphysis and metaphysis of long, short and flat bones (Fig. 6.4). Spongy bone has a relatively different organization of interconnecting trabecular systems. The lamellae in this system are disorganized. Biomechanical durability of spongy bone is therefore less than that of the compact bone. Bone marrow stem cells reside in the bone marrow cavity in order to contribute to blood cell

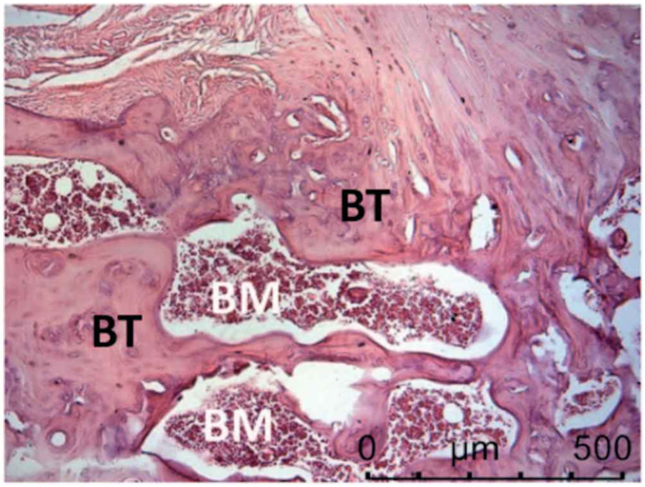

FIGURE 6.4 The bone remodeling area is consisting both spongious bone with trabeculae (BT) and the bone marrow (BM) cavity (100x, Haematoxylin Eosin).

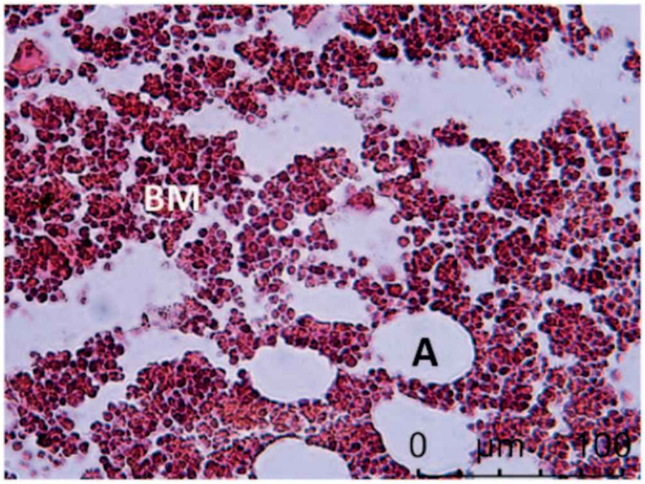

FIGURE 6.5 Bone marrow (BM) cavity with adipocytes (A) are observed (400x, Haematoxylin Eosin).

production (Fig. 6.5). Reticular fibers and adipocytes are also accumulating in spongy bones. Likewise, cortical bone osteocytes reside in their lacunae individually in trabecular bones.

The relation between skeletal muscle mass and bone mineral density can be identified using a dual-energy X-ray absorptiometry device (Lebrasseur et al., 2012; Fornelli et al., 2016). Measuring the microstructure and geometry of both cortical and trabecular bones is only recently possible with software.

Immature (woven) bone

Immature bone basically develops during the intrauterine period or after trauma during the healing stages. Woven bone is observed when fracture repair or bone regeneration occurs. Woven bone is mechanically weak when compared to cortical and or trabecular bone (Clarke, 2008). Immature bone is characterized by the presence of irregular arranged collagen fibers and lack of lamellae. During development, immature bone is replaced by mature bone. In addition, immature bone contains mainly cells, blood vessels and ECM in comparison with that of a mature bone.

Gross Anatomy of Bone

Periosteum and Endosteum

The outer surface of the bone is enveloped by the periosteum, which is a blood-rich, fibrous, irregular dense connective tissue. During development, the periosteum histologically consists of two different layers. The outer layer of the periosteum is called the outer fibrous layer and it involves mainly fibroblasts with type I collagen fibers and small percentage of elastic fibers. The outer fibrous layer is the fibroblast-rich part of the periosteum and it is not calcified. The inner layer of the periosteum is also known as cambium layer, which contains mostly blood vessels. The cambium layer has osteogenic and chondrogenic potential. Blood vessels therefore branch into the whole bone that supplies Volkmann and Haversian canals. Cambium layer is also an irregular dense connective tissue that is rich in cells (Fig. 6.6). Throughout the bone development and growth, it plays a key role in bone remodeling and as bone matures, the cambium layer gets thinner. If a bone injury or fracture occurs, osteoblast activity increases in this part of the bone. Periosteal thickening is also a sign

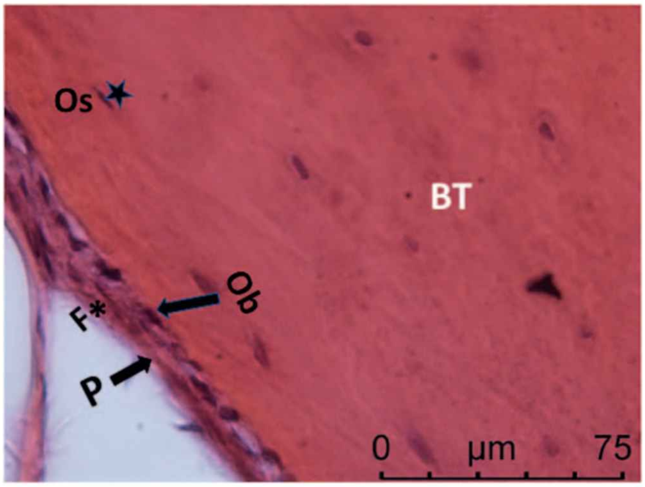

FIGURE 6.6 Bone tissue (BT) that is surrounded by periosteum (P) consisting of fibroblasts (F*) is presented at higher magnification. Note the osteoblasts (Ob) beneath the periosteum and osteocytes (★) in their lacunae (630x, Haematoxylin Eosin).

of pathological conditions such as stress fractures and/or tumor conditions.

The endosteum covers the outer surface of the trabeculae of spongy bones and inner surface of compact bones. It is a single layer of bone epithelial cells and comprises reticular connective tissue (Fig. 6.7).

Composition of the bone tissue

Bone is a metabolically active and highly mineralized tissue. Mineral components consist of 60% of the bone mass. The mineral phase is not only composed of calcium (Ca^{2+}) but also phosphate (PO_4^{3-}) and a small percentage of carbonate (CO_3^{2-}). Additionally, organic components of the ECM constitute about 40% of the volume of the bone.

Cells of the bone tissue

Bone tissue associates with five different types of cells (Downey and Siegel, 2006; Datta et al., 2008):

Osteoprogenitor cells

Osteoprogenitor cells, which originate from MSCs and differentiate into osteoblasts. They also have potential to differentiate into fibroblasts, adipocytes, chondrocytes and muscle cells under appropriate circumstances. Osteoprogenitor cells are located on the endosteal and periosteal surface of the bone and inner surface of the Haversian canals (see Fig. 6.7). Some osteoprogenitor cells transform into osteoblasts after being divided by mitosis. Osteoprogenitor cells are activated during the bone remodeling process or regeneration of injury. Some of the transcription factors such as core binding factor alpha-1 and osteoblast-specific genes like bone morphogenic factor (BMP) and transforming growth factor-β (TGF-β) play crucial roles throughout the processes.

Osteoblasts

Osteoblasts are derived from osteoprogenitor cells. Some mature osteoblasts originate from a group of mesenchymal stromal cells (Marie and Cohen-Solal, 2018). Osteoblasts secrete the components of ECM of the bone. In other words, they synthesize non-mineralized osteoid, which is comprised type I collagen, osteoprotegerin (OPG), macrophage-colony stimulating factor, glycosaminoglycans, proteoglycans and glycoproteins like osteocalcin (OCN) – responsible for matrix calcification – and osteopontin (OPN). Apart from these, osteoblasts also produce alkaline phosphatase (ALP), which contributes mineralization. Once osteoblasts are surrounded with ECM, they are referred to as osteocytes (Fig. 6.8, see also Fig. 6.6).

Active osteoblasts have a well-developed Golgi complex and euchromatic nucleus. Additionally, osteoblasts produce cytoplasmic secretory granules, which consist of ALP and pyrophosphatase. Osteoblasts get in contact with each other and osteocytes via gap junctions. These connections are responsible for the regulation of metabolic responses by way of both chemical and physical stimuli.

Epigenetic studies about osteoblasts become significant, especially on regulation of gene transcription of osteogenic cells. Several transcription factors such as Runt-related transcription factor 2 (Runx2) (Komori, 2008), activating transcription factor 4 (Karsenty, 2008), activator protein 1 (Wagner, 2002), and osterix family members (Koga et al., 2005; Marie and Cohen-Solal, 2018) provide osteoblastic maturation. Lian et al.

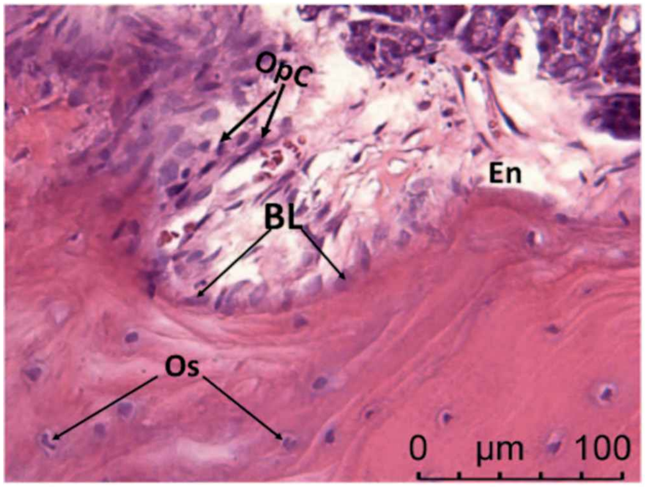

FIGURE 6.7 In bone regeneration area, along with endosteum (En), bone lining cells (BL) are observed. Osteoprogenitor cells (OpC), initiating intramembranous ossification are seen as well (400x, Haematoxylin Eosin).

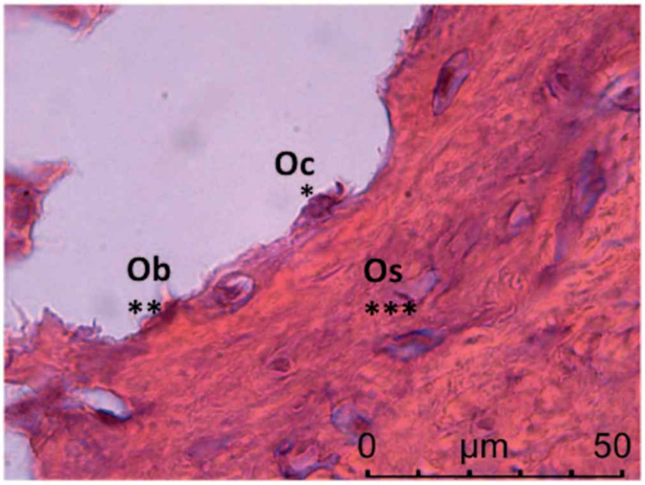

FIGURE 6.8 Along with endosteal surface both osteoclasts (*Oc) which have acidophilic cytoplasm and multiple nuclei and osteoblasts (**Ob) with ovoid shape can be viewed at higher magnification (1000x, Haematoxylin Eosin).

demonstrated that a series of microRNAs (miRNA) can control the osteoblastic differentiation (Lian et al., 2012). Li et al. also revealed that non-coding miRNAs can be used as a target for osteolytic diseases (Li et al., 2018).

Bone lining cells

Bone lining cells are squamous cells that cover the endosteal region (Fig. 6.9). Studies in recent years have indicated that bone-lining cells have had an important role in bone remodeling and hemopoiesis (Farr et al., 2017; Marie and Cohen-Solal, 2018). Bone lining cells arise from osteoblasts and are activated by the parathyroid hormone (PTH) (Kim et al., 2012), fibroblast growth factor 2 and mechanical load (Matic et al., 2016). Matic et al., reported that in the absence of osteoblasts, bone lining cells contribute to bone formation (Matic et al., 2016). They also demonstrated that bone-lining cells promote bone remodeling. Streicher et al. recently stated that estrogen controls bone remodeling by regulating the expression of receptor activator of nuclear factor kappa B (RANKL) which is responsible for the bone resorption (Streicher et al., 2017). They also identified that the suppression of RANKL expression in bone lining cells was observed in estrogen deficient mice where the bone resorption is noticed.

Osteocytes

Osteocytes are the mature cells of the bone tissue, which reside in lacunae. They get in touch with each other owing to canaliculi which are tiny tubes extending along the ECM (see Figs. 6.6, 6.7). Besides, adjacent osteocytes get in contact with each other via gap junctions. Canaliculi allow the transfer of nutrients and oxygen by diffusion. Exchange of minerals and ions are provided by a process named as osteocytic osteolysis. Once the metabolic activities of osteoblast start to decline after secreting ECM components, they differentiate into osteocytes. They have heterochromatic nucleus and limited number of Golgi complexes and granular endoplasmic reticulum.

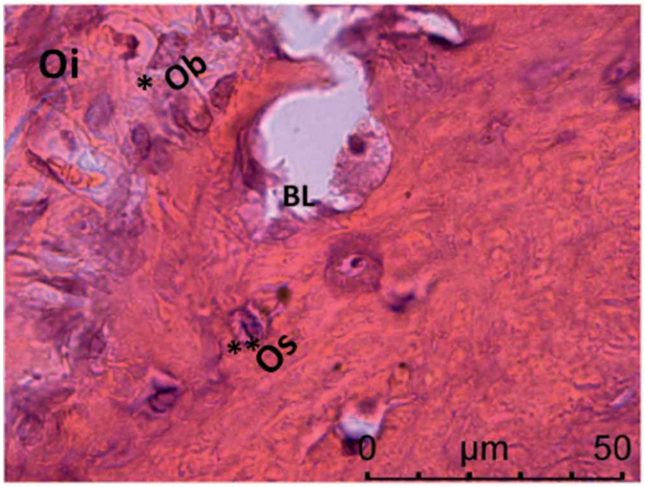

FIGURE 6.9 Intramembranous ossification is presented with osteoid (Oi) secreting osteoblasts (*Ob) and bone lining cells (BL) at endosteal surface. Osteocytes (**Os) are trapped in their lacunae (1000x, Haematoxylin Eosin).

Besides, both skeletal muscle mass and compact bone are controlled by the mechanical influence which is particularly occurs at the load-bearing regions like lumbar spine, tibia or femoral neck. Cells respond to the mechanical energy in terms of a biochemical or a structural change in compact bone. Osteocytes specifically mediate the mechanotransduction process in order to maintain the bone homeostasis. Osteocytes are surrounded by the ECM and for this reason the extracellular fluid flow creates a shear stress on the osteocyte (Temiyasathit and Jacobs, 2010; Fornelli et al., 2016). Mechanical forces are important for the homeostasis of bone. Bone loses strength in gravity-free environment. Osteocytes are important in communication and release information in necessity of repair or regeneration.

Osteoclasts

Osteoclasts are derived from granulocyte-macrophage progenitor cells that are found in bone marrow. Multinucleated osteoclasts have several unique features that separate from other bone cells. They have a diameter of 40–150 μm and acidophilic cytoplasm. They are capable of resorbing the bone. Furthermore, osteoclasts provide the balance between bone formation and bone resorption where bone is being remodeled or destroyed (or damaged). These cells are located in or near the surface of the compact bone marrow cavities known as *Howship Lacunae* (see Fig. 6.8).

Osteoclasts differentiate by virtue of the interaction between mononuclear hematopoietic stem cells and the monocyte/macrophage colony-stimulating factor (M-CSF) and tumor necrosis factor (TNF) which osteoblasts secrete. During this process, expression of nuclear factor kappa-light-chain-enhancer of activated B cells (NF-κB) and c-Fos transcription factors occurs and RANK is expressed on the osteoclast membrane (Arai et al., 1999). The reciprocal action between RANK and its ligand also promotes various signal pathways for the osteoclast differentiation. On the other hand, osteoblasts produce another protein called OPG in order to protect the skeleton from excessive bone resorption (Boyce and Xing, 2007; Guo et al., 2015). After resorption, osteoclasts communicate with osteoblasts by OPG for new bone formation. OPG competes with RANK to bind RANKL. Guo et al. suggested that bone marrow mononuclear cell (BMMC) transplantation promotes the bone remodeling. It is observed that BMMC transplantation after mid-palatal expansion in rats reduced the RANKL/OPG ratio due to the decrease in RANKL expression. The RANKL/OPG ratio regained in EtR group (expansion, transplantation and relapse group) which means that bone resorption and formation activities returned to equilibrium when compared with other groups (Guo et al., 2015).

Parathyroid hormone stimulates osteoclast differentiation by increasing RANKL expression of the osteoblasts (Silva and Kousteni, 2015). This is also essential for calcium turnover of our body. If a chronic deficiency of PTH takes place, a reduction in remodeling process and an increase in bone density occurs. Studies revealed that treatment of hypoparathyroid with PTH could improve bone remodeling (Underbjerg et al., 2015; Cusano et al., 2016; Silva et al., 2017).

Assuming that bone resorption becomes predominant over bone formation, several choices of treatment may be evaluated. Mac-Way et al., suggested that bisphosphonates inhibit osteoclastogenesis, decrease the fracture risk and bone porosity by increasing the bone mineral density (Mac-Way et al., 2014). In addition to this, Bonani et al., carried out clinical trials in order to promote bone healing. According to the results, the monoclonal antibody against RANKL, denosumab enhances the bone stiffness and density (Bonani et al., 2016). Denosumab has also been reported to increase bone mineral density and prevent bone resorption in glucocorticoid induced osteoporosis (OP), which is the most common form of OP (Benlidayi, 2010; Briot and Roux, 2015). Denosumab mimics OPG by interacting with RANKL, increasing bone density and inhibiting the osteoclastic activity (Schieferdecker et al., 2014; Kondegowda et al., 2015; Hochberg et al., 2018). Lane also stated that denosumab is now used as a monoclonal antibody for the treatment of post-menopausal OP in order to treat osteoporotic fractures (Lane, 2017).

Mechanical stress plays a key role in anabolic signaling pathways (Wang et al., 2015). When a bone is subjected to a mechanical load or combined loads, various cellular mechanisms become activated. In vitro studies reveal that mechanical loading influences osteoblast activity and proliferation (Thompson et al., 2012; Yuan et al., 2017). According to Yuan et al., expressions of ALP, osterix, OCN, Runx2 and several osteogenic proteins are upregulated, whereas the expressions of RANKL and several bone resorption factors are down-regulated (Yuan et al., 2017). With these changes, osteoblast differentiation increases and osteoclast activity decreases (Damaraju et al., 2014; Li et al., 2015).

Monocytes, which are precursors of osteoclasts, immigrate and stick to the surface of the bone. Then, they fuse to each other in order to promote bone resorption (Ishii et al., 2010). Extracellular matrix of the bone is absorbed by the proteolytic enzymes of the lysosomes, which are found in osteoclasts, such as cathepsin K and matrix metalloproteinase (MMP).

Extracellular matrix of the bone tissue

Bone ECM contains mainly type I collagen with non-collagenous matrix proteins such as sulphated glycoproteins and proteoglycans. These matrix components constitute about 35% of the bone, which is known as the organic matrix. The inorganic part of the matrix contains mainly minerals made up of HA crystals. Non-collagenous proteins are also known as the ground substance of the bone and they are necessary for bone growth, development, remodeling and repair. Thus, bone always controls the flow dynamics by gaining and loosing ions in order to provide the mineral homeostasis.

Inorganic extracellular matrix

Inorganic matrix of bone consists of mostly calcium hydroxyapatite [Ca10(PO4)6(OH)2] with less amount of bicarbonate, magnesium, potassium, sodium and citrate ions. Calcium phosphate (Ca3(PO4)2) ions also present in the form of HA crystals. The mineral content is crucial for mechanical properties of the bone. All of the minerals give strength to the bone tissue. As the bone mineral level declines, modulus and strength of the bone decrease and fracture risk increases (D'Amelio et al., 2008; Wang et al., 2010a,b,c).

Organic extracellular matrix

Fibrillar organic matrix: Many types of collagen fibers have been identified in our body. Type I collagen fibers are mainly present in the ECM of bone. Fibers are produced by osteoblasts and collagen synthesis occurs with both intrinsic and extrinsic pathways. It provides strength and flexibility to the bone (Viguet-Carrin et al., 2006). In addition, not only type I collagen fibers but also type III, V, XI and XIII collagen fibers exist. Collagen molecules create a collagen network via covalent cross-linking and they not only organize the fibrillation but also contribute to the mineralization. Therefore, collagen fibers affect the mechanical properties of the bone (Tierney et al., 2009).

Non-fibrillar organic matrix: Bone ECM constitutes a group of non-fibrillary proteoglycan aggregates and multi-adhesive glycoproteins. The non-fibrillar matrix is also known as the ground substance of the bone and they have a crucial role in bone development, growth, remodeling and repair. Non-fibrillar proteins are separated into four groups:

(1) Proteoglycans are consisted of a core protein and several glycosaminoglycans (hyaluronan, keratan sulfate and chondroitin sulfate) covalently attached as side

chains. They provide strength to the bone. Additionally, they manage the inhibition process of mineralization of the bone.

(2) Multi-adhesive glycoproteins refer to a group, which serve for the adhesion of bone cells and collagen fibers to the ground substance. Osteonectins are found for attaching the collagen fibers with the HA crystals. Another multi-adhesive glycoprotein like sialoproteins (such as OPN and sialoprotein I and II) control cell adhesion and calcium phosphate production during the mineralization.
(3) Bone-specific vitamin K-dependent proteins are separated into three groups: OCN, protein S and matrix Gla-protein. Osteocalcin is responsible for capturing calcium from blood circulation and stimulating osteoclasts for the remodeling process. Osteocalcin is released with phosphate ions in matrix vesicles by osteoblasts in order to promote the calcification of the bone. Protein S removes cells undergoing apoptosis. Matrix Gla-protein has critical roles in bone calcification after vascularization.
(4) Growth factors and cytokines are the regulatory factors of the bone. The skeletal muscle-derived cytokines are also called as myokines. They include several proteins like insulin-like growth factor 1 (IGF1), TGF-β, TNF, platelet-derived growth factor (PDGF), interleukins (IL-1, IL-6) and BMP.

It is verified with several studies that IGF1 and IGF2 mediate the anabolic activities of skeletal muscle and bone cells (Yakar et al., 2002; Fornelli et al., 2016). IL-6 and IL-7 are responsible for promoting osteoclastogenesis whereas IL-7 has a crucial role in bone formation as well (Fornelli et al., 2016). Zerbini et al. indicated that IL-1 or IL-6 antagonists such as abatacept or rituximab, or anti-TNF blocking agents such as infliximab can be used for the treatment of rheumatoid arthritis (RA) (Zerbini et al., 2017).

Bone morphogenic factor is specific for bone tissue by promoting the development of MSCs into osteoblasts. Nowadays, in clinical trials, recombinant human BMP-7 (osteogenic protein-1) is used for the patients who have large bone injuries or defects in order to induce bone formation (Ross, 2011; Martino et al., 2015).

Besides, Alford et al. have stated that two proteins called asporin and keratokan also have an interaction with the collagen fibers and minerals (Alford et al., 2015).

Mechanical Properties of Bone

Bone can be considered as a biological material that provides mechanical support. Construction of the bone matrix comprises both organic and inorganic compounds which play crucial roles in responding to mechanical loads (Niu et al., 2017). Since the composition, microstructure and biomechanical features of bones differ according to their anatomical location. The structure of the bone, thus, is known to be anisotropic and heterogeneous structures (Attia and Willett, 2017). This section explains how bone exhibits biomechanical behavior in physiological circumstances and under different loading situations.

Bone as a composite natural material

Bone is affected by five different forces; compression, tension, shear, torsion and bending. Mechanical properties of bone are formed by its behavior against these effects. Compression causes a pressing effect on the bone. Tension causes a stretching effect. Shear force acts in different directions perpendicular to the bone. Shear stress can be caused by both compression and tension forces and because of the anisotropic property of the bone, shear stresses cause bone fractures more rapidly. Bone is less resistant to shear force than it is to tension and compression. Torsion shows a vertical and radial impact to the long axis of bone. Torsion also generates shear stress through rotational forces. Bending forces generate tension on one side of the bone and compression on the other side such as shear and torsion forces. In this force type, compression affects a side of the bone while the tension force affects the other side and the shear strength is formed in the middle of these two forces. Bone resists to stress generated by force. The resulting mechanical stress can be measured in Pascal (Pa) or in force per area (N/m^2) (Wang et al., 2010a,b,c; Fung, 2013; Hart et al., 2017).

Stress causes deformation in tissues and this deformation is defined as strain (ε). Mechanical stress and deformation measurements lead to stress–strain interaction of the bone, which can be measured by dial-gages and/or strain-gages. Mechanical stress and deformation measurements give the stress–strain interaction curve graph of the bone and exhibits the mechanical behavior against force. In this graph, the structure of bone can be recovered without deformation in the elastic region. When the force continues to be applied, the yield point is exceeded. Bone structure is deformed irreversibly in the plastic region and a fracture occurs at the failure point (Fig. 6.10) (Knudson, 2007; Akçalı et al., 2009; Fung, 2013; Oftadeh et al., 2015). Permanent deformations occur in the micro-architecture of the bone with micro fractures. Micro-fracture formation varies depending on age and sex. In elderly individuals and women micro-fracture formation is more common. Although micro-fractures in the cortical bone increase the fracture risk, it has also been shown that resistance to fracture growth is caused by studies (Morgan et al., 2018). The curve shows the Young's modulus and represents stiffness of the bone.

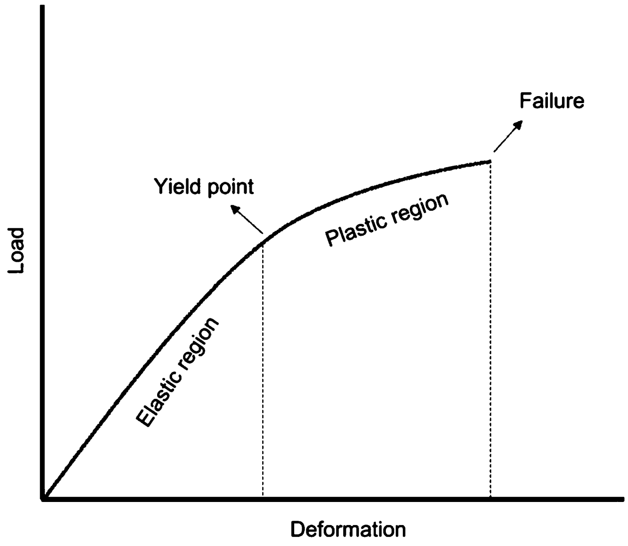

FIGURE 6.10 The load-deformation graph for an elastic material.

The Young's modulus of radial and lateral orientations of the cortical bone is close to each other but higher in the longitudinal orientation. Young's modulus of the cortical bone under the influence of the compression force is lower than the tension force. The mechanical strength (ultimate strain) of the bone is the maximum force that it can stand or the total energy absorbed before fracture (Knudson, 2007; Akçalı et al., 2009; Fung, 2013; Oftadeh et al., 2015).

Stiffness and strength properties of the bone are directly related to bone mineral density. Elasticity of bone is lower due to the structure formed by the calcium phosphate ions it contains. Mineralized bone is therefore more vulnerable to low-energy forces. Collagen affects the toughness property of the bone and shows resistance to fracture formation. The acceleration of the force, the strength and the duration also determine fracture risk. Applied to bone and low but long-lasting forces that do not exceed the point represented by yield point cause fatigue fractures in the bones (Athanasiou et al., 2000; Keaveny et al., 2001; Wang et al., 2010a,b,c).

If the applied force can be absorbed, bone shows adaptive properties against applied forces. Adaptation property of bone is summarized by the Wolff's Law. According to Wolff's Law, mechanical effects change the micro architecture of bone in the context of mathematical laws and bone, thus, regenerates under mechanical stimulation (Keaveny et al., 2001; Knudson, 2007).

Lamellar and collagen fibrils of the cortical bone are regular and therefore show a denser structure. Trabecular bone shows irregular lamellae and pore structure connected to each other. Because of the anisotropic properties of bone, the mechanical strength properties vary depending on the type and orientation of the load, the degree of calcification of the bone, the collagen distribution and anatomical location (Athanasiou et al., 2000; Keaveny et al., 2001; Wang et al., 2010a,b,c). This change affects stress absorption of the bone. Resistance to deformation and the absorption of total energy before fracture and these effects depend on elasticity, stiffness and toughness properties of the bone, respectively. This behavior is different in cortical and trabecular bones (Athanasiou et al., 2000; Bayraktar et al., 2004; Wang et al., 2010a,b,c; Osterhoff et al., 2016).

Biomechanical behavior of bone

Bone shows different mechanical behavior when force is applied in different directions and this feature is called anisotropy. Both cortical and trabecular bone are anisotropic. Mineral crystal structure and collagen distribution involved in the structure of the bone affect the anisotropic characteristic of the bone (Knudson, 2007; Bankoff, 2012; Fung, 2013).

Bone shows viscoelastic properties. According to this, mechanical behavior of bone varies with the degree of force applied and the duration of force (Table 6.1). When the applied force is fast, the response of the bone becomes more rigid but energy absorbed before fracture is more. When the applied force is slow, the bone shows less rigidity, but the energy that can be absorbed is reduced and fractures occur (Wang et al., 2010a,b,c; Bankoff, 2012; Fung, 2013).

Bone behavior under different loading situations

Bone biomechanics is an area that studies the physical behavior and the deformation of the bone resulting from the applied force. Key biomechanical properties of bone are considered in two groups; intrinsic and extrinsic properties. Intrinsic properties include ductility, stiffness, toughness, strain and mechanical strength of the bone while extrinsic properties indicate the structural behavior of the bone tissue. The two biomechanical properties are important for fracture resistance (Forestier-Zhang and Bishop, 2016). Gürgül et al., also stated that the bone biomechanics involve the changes in fragility of the bone in pathological conditions and the early treatment strategies (Gürgül et al., 2016).

Musculoskeletal tissues exhibit mechanical behavior under various forces and moments. Bone resists against different mechanical forces and stress factors by adapting to them. The mechanical properties and geometric characteristics of bone include; mechanical load type; direction, frequency and rate of loading (Nordin et al., 2012). Several research groups revealed that depending on the load type and the direction of loading, mechanical environment around the bone tissue has an effect on

TABLE 6.1 The elastic moduli (Young's modulus) of the human cortical bone are summarized.

Bone	Load type	Orientation	Young's modulus (GPa)	Ref.
Femur	Tension	Longitudinal	15.6–19.4	Wang et al. (2010a)
Femur	Compression	Longitudinal	15.2–18.1	Wang et al. (2010a)
Femur	Torsion	Longitudinal	3.3–5.0	Wang et al. (2010a)
Femur	Bending (3 point)	Longitudinal	10.8–15.8	Wang et al. (2010a)
Femur	Bending (4 point)	Longitudinal	12.1	Wang et al. (2010a)
Femur	Compression	–	15.5	Athanasiou et al. (2000)
Femur	Tension	–	3.9–11.9	Athanasiou et al. (2000)
Femur	Tension	–	19.9 ± 1.8	Bayraktar et al. (2004)
Tibia	Tension	Longitudinal	18.0–29.2	Wang et al. (2010a)
Tibia	Compression	Longitudinal	15.9–35.3	Wang et al. (2010a)
Tibia	Bending (Cantilever)	Longitudinal	10.6	Wang et al. (2010a)
Tibia	Bending	–	10.8	Athanasiou et al. (2000)
Tibia	Bending (3 point)	–	5.4	Athanasiou et al. (2000)
Tibia	Bending (4 point)	–	6.75 ± 1.0	Athanasiou et al. (2000)
Fibula	Tension	Longitudinal	18.5	Wang et al. (2010a)
Humerus	Tension	Longitudinal	17.2	Wang et al. (2010a)
Radius	Tension	Longitudinal	18.5	Wang et al. (2010a)
Ulna	Tension	Longitudinal	18.4	Wang et al. (2010a)

regeneration and degeneration of the whole tissue (Trumbull et al., 2016). Thus, the mechanobiological niche becomes crucial for musculoskeletal regeneration. There are several types of forces: compression, tension, shear, torsion and bending. However, osteocytes, within the bone are exposed to fluid flow stress (Trumbull et al., 2016).

Compression

Compression is a type of force, which has a tendency to compress or shorten a structure in its acting on the tissue (Nordin et al., 2012). Compressive stress appears mainly on a surface perpendicular to the load (Fig. 6.11). Our musculoskeletal tissues, especially bone and cartilage, are under compressive loading.

Bone is often subjected to combine loads. Uniaxial compression and tension tests are used for evaluating the effects of alterations in structure of the tissue. However, they are insufficient tests for determining the anisotropy and other mechanical features of bones (Attia and Willett, 2017). Thus, additional tests with multiple directions and stresses must be applied to bone in order to identify its mechanical behaviors. When the magnitude of the acting force on bone is over the ultimate strength, a fracture may occur. Altered biomechanics of bone can cause various compression fractures and progressive diseases and deformities as well. Compressive forces cause oblique fractures, which are diagonal to bone's long axis, despite the osteonal and collagen fiber arrangement. There are two

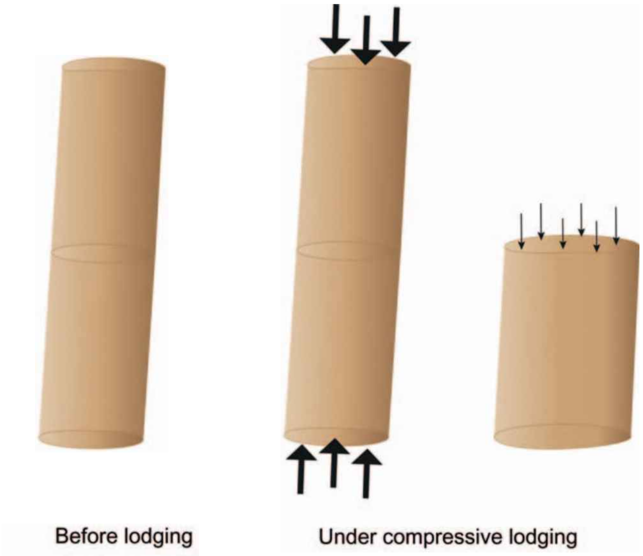

FIGURE 6.11 Schematic representation of a bone before loading and under compressive loading.

patterns of fracture: fatigue and pathological fracture. Fatigue fractures occur with a repetitive loading and the damage appears at a faster rate. Repetitive loading declines the tensile strength more than the compression strength. Fatigue fractures are generally seen in athletes or military personnel carrying high amount of loads. Few studies have been undertaken on the fatigue behavior of the bone (Cotton et al., 2005; Dendorfer et al., 2008). In order to evaluate its biomechanical behavior, demineralized bone have been tested and elastic modulus and strength of bone have been evaluated (Novitskaya et al., 2013).

Compression fractures are generally seen in osteoporotic bones. Since people with OP have decreased bone strength, fracture threshold of these patients also shows a significant descending tendency. Clinically, kyphoplasty surgery is applied for the patients with osteoporotic fractures in order to restore the damaged vertebra's height (Tobias and Johnston, 2013). Moreover, percutaneous vertebroplasty is applied for minor trauma and complications (Yang et al., 2017). Yang et al., revealed that high viscosity bone cement would be beneficial as a personalized treatment in order to improve the therapeutic effect.

Donnally and Dulebohn stated that when a compression fracture occurs in the spine, additional stress factors can be seen on other vertebral bones and the spine biomechanics may change (Donnally and Dulebohn, 2018). Because the spine is the most important component of the skeletal system, spinal compression fractures and spinal cord injuries must be treated immediately with nonsurgical or surgical treatments. In recent years, it is hypothesized that coupling agents like TGF-β1 can be used as an effector on bone reconstruction (Kasagi and Chen, 2013). Zhao et al., demonstrated that a spinal cord injury induced by a compression fracture causes an alteration in expression of miRNAs and they also reported that miR-185 and TGF-β1, which is synthesized by osteoblasts and stimulates the synthesis of ECM components, are expressed in patients with the spinal cord injuries induced by spine compression fractures (Zhao et al., 2017).

Tension

Tension is a type of force, which produces a narrowing and elongation of a structure. In other words, during tensile loading, opposite and equal forces are applied outward from the structure (Fig. 6.12). Thus, the tensile stress occurs inside of it. Maximal tensile forces appear on a plane perpendicular to the load. Consequently, fractures can occur along the structure. Moreover, these forces tend to be influenced by the microstructure of the bone, e.g. immature bone.

Mechanical tension is a regulatory factor in bone metabolism (Kang et al., 2012). Several researchers revealed that mechanical tension has a positive impact on osteogenesis of MSCs by activating various cellular pathways (Bonewald and Johnson, 2008; Tan et al., 2015). Wu et al., identified that long non-coding RNA H19 promotes the osteoblastic differentiation of human bone marrow MSCs during tensional loading (Wu et al., 2018).

Since bone as a composite natural material of the musculoskeletal system resist large loads, such as compressive and tensile loads, it can adapt to greater strengths. Both tension and compression tests are used as standard uniaxial tests in which a structure is loaded under an axial load (Wang et al., 2010a,b,c). The difference between tension and compression tests results from the nonhomogeneous anisotropic composite construction of bone. It is also known that the ultimate strength values of the bone differ from each other when tested in other conditions because of its nonhomogeneous anisotropic construction (Fung, 2013).

Shear

In contrast to tensile and compressive forces, during shear loading, the force is applied parallel or tangential to the surface of the structure and a shear stress, therefore, occurs inside the structure (Fig. 6.13A). Shear load also tends to deform the internal structures. Its deformation behavior typically depends on the type of stress applied on the structure. Shear fractures are generally seen in cancellous bone (Nordin et al., 2012). However, Tang et al.,

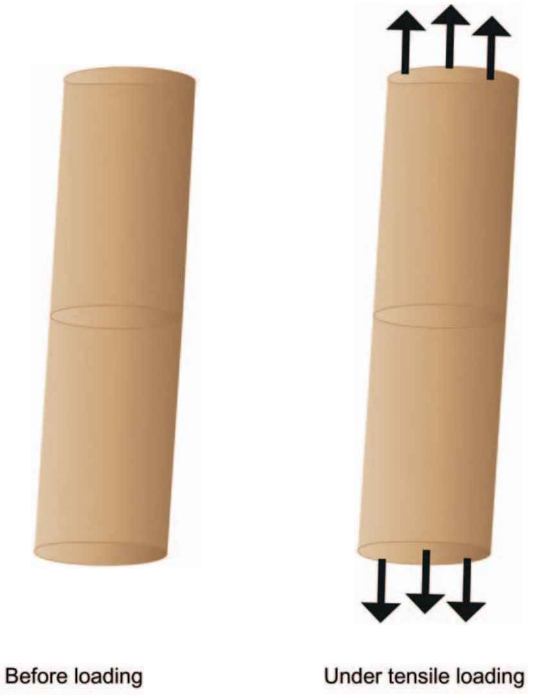

FIGURE 6.12 Schematic representation of a bone before loading and under tensile loading.

evaluated the biomechanical behavior of human cortical bone under shear loading and the relevance between the bone microstructure and its fracture behavior (Tang et al., 2015). They revealed that with a highest shear strength, human cortical bone acts as an anisotropic structure and a shear-induced micro cracking resulted from the lamellar structure, i.e. Haversian systems, of the cortical bone (Fig. 6.13B).

Fluid shear stress (FSS) is a mechanical loading that stimulates bone cells and ECM components under physiological conditions (Young et al., 2009, 2010; Li et al., 2012). Fluid shear stress affects the mineralization process of the bone. The shear forces induce collagen mineralization; amorphous calcium phosphate formation and HA organization (Niu et al., 2017). Shear stress has, furthermore, a positive impact on fluid flow and new bone formation. Tiwari et al., found out that maximal osteogenic response due to FSS has been observed around the central axis of the model (Tiwari and Prasad, 2017). Stavenschi et al., revealed that fluid flow induced shear could affect the osteogenic lineage of MSCs and influences the bone formation via a mechanical stimulus (Stavenschi et al., 2017).

Osteocytes enhance bone adaptation against mechanical loading (You et al., 2008). Moreover, mechanical compressive forces have been found to induce osteoblasts to express IL-17, which is an important cytokine for the osteoclast differentiation and activation. Thus, osteocytes induce bone remodeling by stimulating the expression of IL-17 via fluid flow stress. Liao et al., examined the role of IL-17 and fluid flow stress in bone remodeling and reported that IL-17A enhanced osteocyte cell proliferation and expression of RANKL and tumor necrosis factor α (TNF-α) inclined (Liao et al., 2017). They also stated that FSS upregulated the expression of OPG in osteocytes for the remodeling process. With several experiments, it has been proven that Ca^{2+} permeable membrane ion channels, especially transient receptor potential cation channel subfamily V member 4 (TRPV4), stimulate and transduce the differentiation of human MSCs due to FSS. It has also been verified that TRPV4 channels mediated the Ca^{2+} influx and osteogenic differentiation via the FSS (Hu et al., 2017).

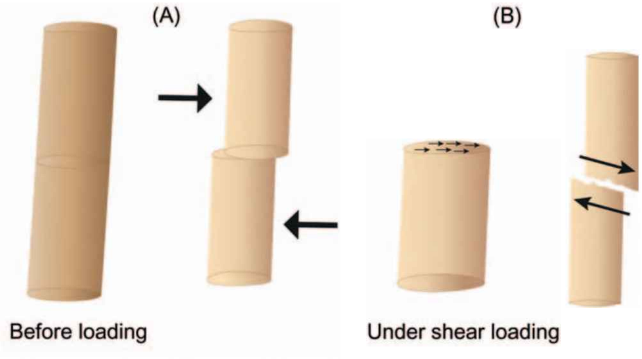

FIGURE 6.13 Schematic representation of a bone (A) under shear loading and (B) a fracture due to excessive shear force.

Torsion

Shear properties of a structure can be deduced with a torsion test. Torsional forces are applied to a structure, which causes it to twist about its long axis. The shear stress created in the bone is proportional to their distance from the center axis of the structure (Fig. 6.14). Thus, as the distance from the center axis gets farther, the shear stress increases in magnitude (Nordin et al., 2012; Tobias and Johnston, 2013). In addition, maximal shear stress has an effect on surface parallel and perpendicular to the central axis.

Fracture pattern for the bone under torsional loading demonstrates that an initial crack is formed parallel to the central axis of the bone, i.e. along the long axis of the bone. A second crack is then formed along the surface where the tension is maximum in magnitude (Nordin et al., 2012).

As the loading condition and the magnitude of the force create specific fracture morphology, the determination of biomechanical response and the fracture mechanism become important. Accordingly, Bertocci et al., carried out an experiment which includes three-point bending and torsion tests on immature porcine femora and

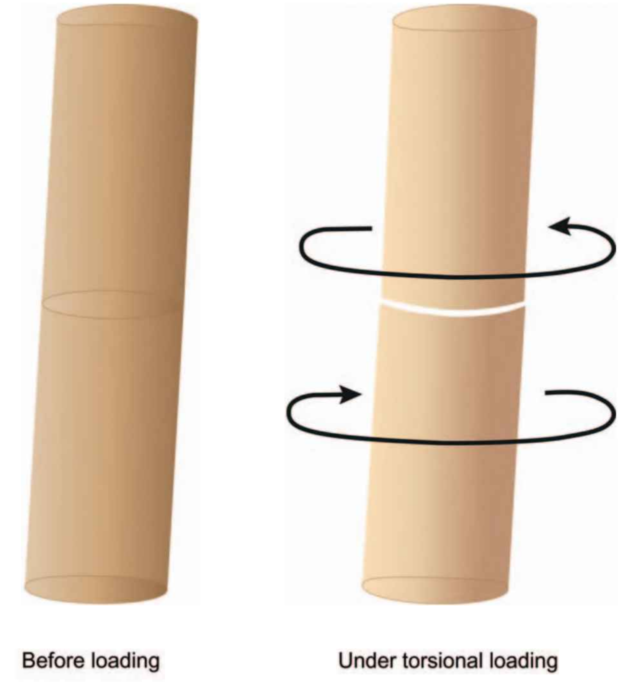

FIGURE 6.14 Schematic representation of a bone before loading and under torsional loading.

the fracture morphologies (Bertocci et al., 2017). They found out that spiral fractures have been formed on the specimens, which have been tested in torsion.

Bending

Bending forces is a combination of tension and compression forces because tensile stress and strain have an effect on one side of the structure whereas the compressive force and strain have an effect on the other side. Thus, one side of the structure becomes convex shaped and the other side which is under compression becomes concave shaped. As in torsional stress, the magnitude of the stresses on the bone gets higher with the increase in distance from the central axis.

There are two common types of bending forces: three-point forces (three forces) and four-point bending (four forces) which result in bending on a structure. Three forces acting on the bone may create a fracture at the side of load applied (Fig. 6.15A). However, the test poses problems because the variation in cross-section of the long bones leads to a higher shear stress at the middle of the bone (Cheong et al., 2017). Furthermore, a failure can occur due to shear stress instead of tension. Thus, the test must be applied to the samples which have a uniform structure (Athanasiou et al., 2000). Four forces are applied at each end and at the points between the end points and a pure stress is applied on a bone of constant and symmetrical (Fig. 6.15B). Cheong et al., tested of the immature long bones in bending and torsion and identified the biomechanical behavior of it (Cheong et al., 2017). Following the researches, they observed both transverse fractures, which represent the low-energy events, and oblique fractures, which reflect the higher energy. In addition, in four bending test, the immature bone specimens vary in fracture patterns, whereas, in torsional loading, multiple fractures and a change in obliquity are seen with the increasing strain rate.

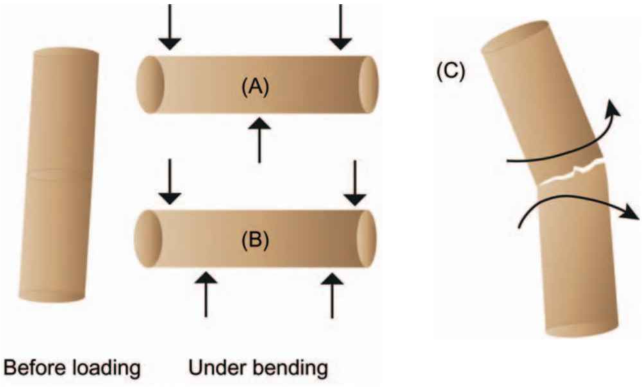

FIGURE 6.15 Schematic representation of a bone (A) under three-point forces, (B) four-point forces and (C) a transverse fracture due to excessive bending.

When the bone is loaded with bending forces, transverse fractures may occur (Tobias and Johnston, 2013) (Fig. 6.15C). The opposite side of the fracture on a cortical bone can also be broken via small bending forces, whereas larger forces can split the entire bone by damaging the tissue and vascular structure of the bone.

Bone tissue in different life stages

Skeletal system derives from different origins during intra-uterine development. Intra-embryonic mesoderm gives rise to precursors of skeletal system components as an embryo is growing.

Development of bone tissue

At the third week of embryogenesis, bone tissue appears as composed of mesenchymal cell condensation. Histogenesis of bone tissue can be seen as membranous and endochondral ossifications.

Membranous ossification

Mesenchymal cells gather and condense in early life stages of the embryo. This condensation gives rise to the first immature form of bone tissue after vascularized and immigrated by bone precursor cells. Mesenchymal cells develop into osteoblasts in time and unmineralized matrix is called as osteoid. Calcium phosphate appears in the matrix and osteoblasts are kept in lacunae converting to osteocytes during mineralization. The matrix and ingredients form more complex constructions as maturation of bone carries on. For example, the Haversian system that includes osteocytes, concentric lamellae and blood vessels appear in the matrix (Moore et al., 2013) (see Figs. 6.7 and 6.9).

There are studies reporting that during osteoblast and osteoprogenitor cell mediated ossification, some proteins, enzymes and signaling pathways play important roles (Pearlin et al., 2018). In case of Runx2 gene or BMP-7 absence, skeletal system development can be interrupted and urinary system and circulatory system disorganizations are obtained as well (Pearlin et al., 2018).

Facts on membranous ossification are recently researched due to the requirements of new improvements in regenerative medicine. Bio-safe 3D scaffolds and polymers that are combined with hydrogels and BMP-2 have been reported to have potential for further osteogenic development when compared to poly(ε-caprolactone) (PCL) scaffolds (Dong et al., 2017).

Endochondral ossification

New bone formation in the presence of a cartilage plate is defined as endochondral ossification. Endochondral ossification takes place in the physis of long bones. Stages of the endochondral ossification process are through resting, proliferation, hypertrophy, calcification and ossification zones (Fig. 6.16). In the resting zone, chondrocytes are observed in their lacunae. In the proliferation zone, isogenous chondrocytes groups increase in number. In the hypertrophy zone, size of chondrocytes increases and when it comes to the calcified zone we observe calcification followed by ossification (Fig. 6.17). During endochondral ossification, bone precursor cells are mobilized through vessels originating from the periosteum. Inorganic components of bone matrix are also delivered along with the blood supply (Moore et al., 2013).

Remodeling

Bone tissue is actively remodeled throughout its life span. Mostly it is regulated by cells of the bone and with contribution of the matrix and the microenvironment (Fig. 6.18). Remodeling is staged by continuous new bone formation and resorption (Florencio-Silva et al., 2015). In addition to main bone cells (osteoblast, osteocyte, osteoclast), stem cells can be precursors of bone remodeling (Han et al., 2018). Remodeling is a needed ongoing process for each healthy person. Basically the procedure consists of removal of old tissue by osteoclasts and replacement by newly formed tissue by osteoblasts (Han et al., 2018).

Bone cells can release signaling proteins and cytokines for tissue homeostasis. Osteocytes and osteoblasts mostly release M-CSF, RANKL, Wnt gene family 5A (Wnt5A) and 16 (Wnt16). Sclerostin (SOST), which is secreted by osteocytes is also known to suppress osteoclastic activity. Osteoclasts on the other hand secrete BMP-6, collagen triple helix repeat containing 1, EphrinB2 (EFNB2) and Cardiotrophin-1. Osteoclastogenesis is usually induced by osteocytes that sense loss of integrity of the bone tissue. After osteoclasts resorb the disrupted and degenerated structure, angiogenesis takes place in remodeling. Vascular endothelial growth factor A (VEGFA) that is released by osteoblasts not only regulates endothelial cell activation but also allows new vessel formation. Bone cells also contribute to angiogenesis by releasing paracrine factors (Han et al., 2018).

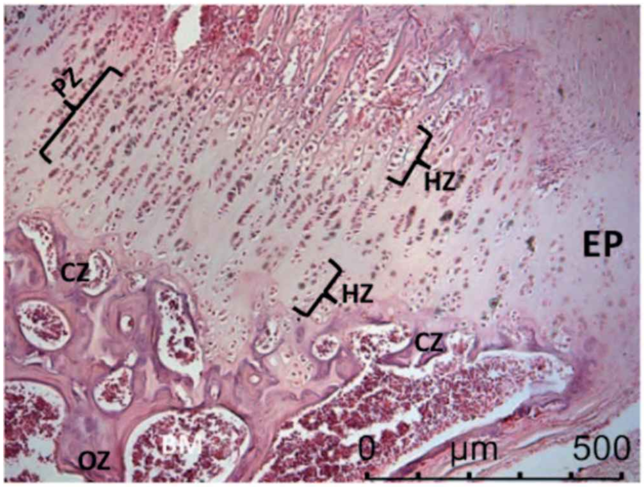

FIGURE 6.16 Endochondral ossification possess proliferation zone (PZ), hypertrophy zone (HZ), calcification zone (CZ) and ossification zone (OZ) are observed at epiphyseal plate (100x, HE).

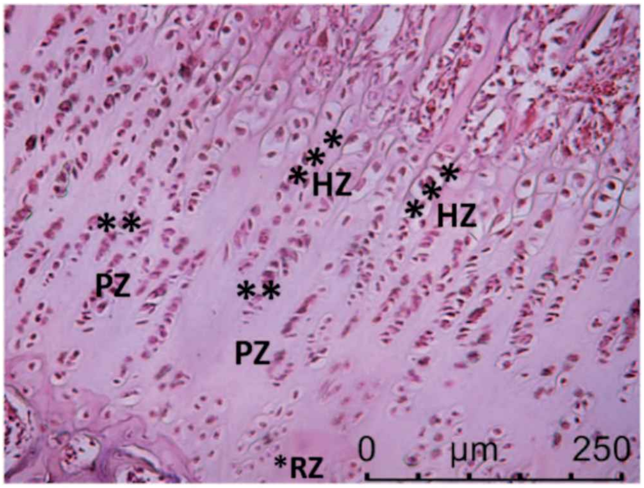

FIGURE 6.17 High magnification micrograph of cartilage plate presenting resting zone (RZ*), proliferation zone (PZ**) and hypertrophy zone (HZ***) in endochondral ossification (200x, Haematoxylin Eosin).

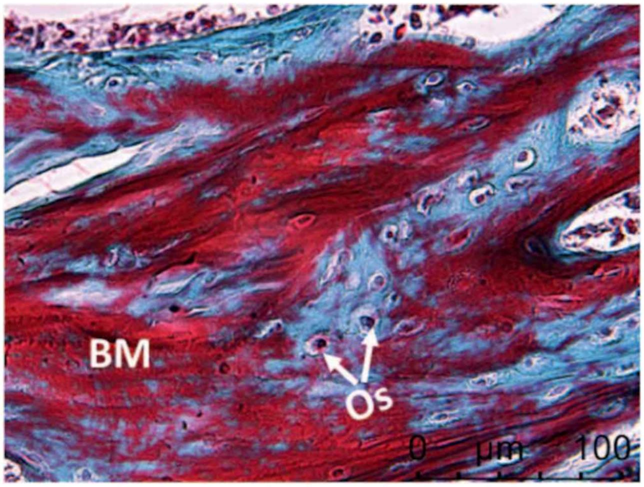

FIGURE 6.18 In bone tissue remodeling, red and green areas of newly formed bone matrix (BMx) are presented. Osteocytes (Os) in their lacunae are noticeable (400x, Masson's Trichrome).

Wnt signaling pathway and SOST is reported for being important in bone metabolism. Recent studies revealed that in absence of Wnt16, cortical bone development failed. Wnt signaling is supposed to be displaying critical role in bone homeostasis (Han et al., 2018). Cardiotrophin-1, belongs to the IL-6 family and released by osteoclasts. It is needed for bone tissue remodeling for initiating the process and it also interacts with Runx2 (Brommage and Ohlsson, 2018).

The nuclear factor of activated T cells encodes EFNB2 target gene in osteoclasts, moreover its receptor (EphB4) is found in osteoclasts. The interaction of these receptor-gene couple leads to bone formation and osteoclast inhibition (Brommage and Ohlsson, 2018). In bone resorption, BMPs is believed to have significant roles for bone formation through osteoclasts (Brommage and Ohlsson, 2018).

As particularly studied in OP disease; SOST has been reported to have critical roles for stimulating osteoclastogenesis and inhibition of osteoblastic activity. Osteocyte derived SOST is thought to be one of the major factor among bone tissue adaptation mechanisms (Han et al., 2018).

Adaptation of the bone tissue to pathological conditions

Bone tissue responds to unexpected harms by different modalities; including fractures (in mature and immature bone), orthopedic interventions, ischemic diseases (Osteomyelitis), hereditary diseases (Osteogenesis imperfecta, Paget's disease), metabolic diseases (Osteoarthritis (OA), OP), bone tumors (primary and secondary) and surgical extraction of bone (Zreiqat et al., 2015; Kameo et al., 2018). Bone possesses an entire collectivity with its cells and ECM. Its microenvironment displays a good regenerative and adaptive behavior to pathological conditions. Arrangement of bone tissue along with its cells and matrix adapts to pathological conditions. The most important role of osteocytes in tissue matrix is providing maintenance of homeostasis. Osteocytes are capable to join bone repair by numerous metabolic pathways such as apoptosis, osteoclastogenesis, osteolysis, angiogenesis, mineralization and bone formation with other bone tissue cells (Zreiqat et al., 2015; Kameo et al., 2018). The role of the microenvironment of the matrix still needs attention (Zreiqat et al., 2015).

Apoptotic response by bone cells

Apoptosis that is observed under physiological conditions is also seen in pathological situations at the microenvironment of bone tissue (Mollazadeh et al., 2015). Two pathways usually monitor apoptosis. The first one is the "extrinsic pathway", which is comprised of the cellular surface death receptor–ligand interaction and the second one is the mitochondrial alterations caused by the intrinsic pathway (Mollazadeh et al., 2015). The ratio of apoptotic osteocytes and osteoblasts is expected to increase spontaneously while the cells get older (Mollazadeh et al., 2015).

Osteocyte apoptosis is not only demonstrated by a single cell reply to pathological conditions in damaged bone but it also stimulates osteoclasts (Ye et al., 2017) that helps the removal of destructed tissue and reclamation of the bone matrix (Zreiqat et al., 2015). Usually osteocytic apoptosis is caused by stress micro-fractures, which will lead later to the death of osteocytes and induction of osteoclasts (Mollazadeh et al., 2015). Micro-fractures can initiate a range of cascades that include ending up with both elimination and replacement the bone tissue matrix (Zreiqat et al., 2015). Since, matrix itself is hosting osteocytes in their lacunae and free radical savers cannot reach this area, apoptosis of osteocyte not only ends up with cell disturbance but also gives rise to osteoclastogenesis (Zreiqat et al., 2015).

Individual cell of bone responds to apoptosis differently (Mollazadeh et al., 2015). For example, caspases (initiators: caspase-8, -9; executioners: caspase-3, -9) take part to be main regulators in osteoblastic apoptosis. Pro- and anti-apoptotic proteins such as Bax, Bad, Bid and Bcl-2, Bcl-xL are considered to be part of the procedure (Mollazadeh et al., 2015). Almeida reported that increased reactive oxygen species and oxidative stress levels induce apoptosis of osteoblasts while Forkhead box O3 reduced osteoblastic apoptosis and increased the number of osteoblasts (Almeida, 2012).

Bone tissue degradation, that is originated by osteocytic apoptosis and presented with inflammatory mediators TNF-α, IL-6 and IL-1 release, leads to osteoclast activation (Mollazadeh et al., 2015). Along with cell disruption, accompanying matrix degradation can occur due to MMP mutation of collagen fibers (Mollazadeh et al., 2015). Age-related osteocytic apoptosis is allied with reduced amounts of RANKL and SOST for decomposed tissue reconstructing (Almeida, 2012).

Apoptosis of osteoclast is controlled by Fas ligand and TNF-related apoptosis-inducing ligand (Mollazadeh et al., 2015). Apoptosis of osteoclast is obvious in diseases such as Paget's disease of bone, hyperparathyroidism, postmenopausal OP and RA (Mollazadeh et al., 2015).

Osteoclastogenesis

Osteocyte related apoptosis triggers the release of the RANKL system members and initiate osteoclastogenesis (Mollazadeh et al., 2015). Osteoclasts develop from myeloid cell sources so the RANKL is a necessity for activation (Findlay and Atkins, 2011). Osteoclastogenesis could be organized by osteocytic activities in mature bone (Nakashima et al., 2011; Xiong et al., 2011).

After osteocyte mediated apoptosis, which is caused by micro-fractures, elevated RANKL expressions are observed in the bone tissue (Tatsumi et al., 2007). Resorption of the matrix occurs as increasing osteoclastic activity becomes dominant in the tissue (Tatsumi et al., 2007). RANKL that is activated by osteoblasts, osteocytes and M-CSF and Wnt5A and Wnt16 influences osteoclastogenesis (Han et al., 2018). Sclerostin that is a protein expressed by the SOST gene of osteocytes promotes RANKL by osteocytes and allows osteoclast-based bone remodeling (Wijenayaka et al., 2011; Shu et al., 2017).

Angiogenesis

Angiogenesis is not only seen in musculoskeletal development of embryonic life but it is also important for bone formation, regeneration and fracture healing (Portal-Núñez et al., 2012). Individual cells of bone (osteocytes, osteoblasts, osteoclasts) modulate the process by dissimilar manners. Without angiogenesis; bone formation, regeneration and fracture healing would not be possible. Necrotic tissue is removed by angiogenesis. Immature osteoblast and chondrocyte originated VEGFA causes endothelial cell migration, growth and endurance while pre-osteoclast-secreted platelet-derived growth factor-BB induce development of vessel and new bone (Han et al., 2018).

Osteolysis and mineralization

A cycle of matrix degradation is followed by new tissue formation during bone tissue homeostasis without causing bone mineral density loss. Activation of NF-κB and interaction with RANK play an important role to initiate bone resorption and osteoblastic activity inhibition when osteoclastic activity is in the foreground. Activation of the RANKL system also initiates an inflammatory process including TNF, IL-1b and IL-6 expression. As osteocytes give rise to these inflammatory molecules, each cell of the bone tissue affects the osteolytic cascade pathway as well. Bone tissue, as a skeletal organ that is providing protection and movement, also displays as a metabolic organ, which contributes to calcium homeostasis. Thus, lysis of bone matrix would help balancing the blood calcium and also phosphate levels (van Niekerk et al., 2018).

Researchers furthermore showed that osteocyte derived carbonic anhydrases, proton pumps, cathepsin and MMP-13 enzyme levels elevated during lactation. Osteocytes are therefore considered to remove bone tissue matrix alike osteoclasts however further studies are essential to verify this process (Qing et al., 2012). Osteocytic osteolysis may also stand suitable for regulating the balance of calcium levels and likely to depend on hormonal activity like lactation and also PTH receptor signaling on osteocytes (Qing et al., 2012).

Proteins expressed by osteocytes may likewise help bone matrix mineralization. Acidic serine aspartate-rich MEPE related released from osteocytes and osteoblasts may aggregate calcium-phosphate from the matrix (Zreiqat et al., 2015). Osteopontin does also form new bone by matrix mineralization (Zreiqat et al., 2015).

Bone formation

Bone tissue can regenerate and remodel itself along with its cells, microenvironmental signals, endosteum, periosteum and blood vessels (Murao et al., 2013). The bone formation process could be primary or secondary. Primary formation usually happens prior to pre-fixed fractured bone endings. Osteoclastic activity plays important role in this formation and then osteoblast location to that cutting zones takes over the healing process. In secondary bone formation, the signals come through the periosteum and the surrounding connective tissue that act for the organizing of new bone formation (Zreiqat et al., 2015).

The process can be followed as:

Granulation formation: After bone fracture, the surrounding soft tissue of the bone and also blood vessels close to the tissue become damaged too. All these processes end up with a hematoma formation. Macrophages and leukocytes coming by blood flow provide initiation of an inflammatory process and this process happens during the first 48 hours of trauma (Runyan and Gabrick, 2017).

Callus formation: Formerly composed granulation tissue becomes crowded with MSCs, then chondrogenic cell formation starts with ECM ingredients including collagens and proteoglycans. Thus, first the soft callus arises. Angiogenesis occurs during the same time and VEGF related pathway becomes in charge for angiogenesis (Marsell and Einhorn, 2011). Approximately a week lasting procedure ends up with a rough callus formation. As in this setting, chondrocytes hypertrophy, which is followed by matrix calcification. Inflammatory cells contribute to the process and maintain angiogenesis by VEGF, BMP, PDGF and TGF-β and osteoblasts that arrive through the blood to join matrix formation (Marsell and Einhorn, 2011; Oryan et al., 2015; Runyan and Gabrick, 2017).

Osteogenesis of callus: Mainly vascularized callus becomes invaded by osteoblasts, osteoclasts and osteocytes. As osteoclasts continue to resorb the rough callus, osteocytes invade into the residue areas to form new original bone tissue (Runyan and Gabrick, 2017; Wang et al., 2017).

Clinical approaches

Several studies focus on bone regeneration and repair. Among them, one of the most applied experimental approaches is bone grafting. Auto/allograft application of destroyed, degenerated, inflamed or destructed bone matrix area may allow new bone formation. Tekin et al. reported that autogenous graft application on mandibular defect area showed more osteoinductive effect compared to xenograft-applied group and caused less foreign tissue reaction (Tekin et al., 2017). However, when autograft sampling is not enough, colleagues need to find solutions with synthetic or allogenic grafts (Bolgen et al., 2014; Ekin et al., 2016; Sirin et al., 2016; Vural et al., 2017). Osteoblasts, osteocytes and osteoclasts contribute to bone regeneration by metabolic pathway activation during graft integration. Cytokines, hormones, growth factors and BMPs accompany tissue regeneration with osteoblastic activity. Bisphosphonates, as being pyrophosphate analogue, are known to prevent osteoclastic bone resorption and they are widely used for therapy of OP, osteolytic bone tumors and Paget's disease of bone (Tekin et al., 2017). According to Tekin et al., bisphosphonate analogue alendronate applied on lay grafts showed efficient osteoblastic activity compared to controls. The same research group reported that alendronate combined autogenous-graft application contribute to new bone formation and protected bone tissue from resorption as well (Tekin et al., 2017).

Dogan et al., defined that hyaluronic acid and collagen conjugated heterologous-grafts for sinus augmentation initiated new bone formation (Dogan et al., 2017). Extracellular matrix components are also useful to repair bone defects. In cranial bone defects, application of genetically encoded BMP-2 MSCs competed with autograft applied groups for regeneration (Vural et al., 2017). Ekin et al., reported collagen/ß-three calcium phosphate and poly(L-lactide)/poly(ε-caprolactone) application supplied nearly as good healing as autograft applied alveolar defects (Ekin et al., 2016).

Osteoporosis (OP)

Massive loss of mineral density of the matrix and structural degeneration ending up with fragility fractures define OP. Osteoblastic bone production and osteoclastic resorption balance are lost in OP. Hormonal activity of PTH, estrogen and androgen alter, which increases osteoclastic activity. Primary and secondary OP are defined clinically. Primary OP is mostly seen at post-menopausal stages of women that is related to loss of estrogen. Secondary OP is related to other metabolic diseases (Ross, 2011).

Estrogen treatment may have side effects (Stapleton et al., 2017). Various studies presented that combined applications of estrogen, bisphosphonates and polyethylene glycol may support bone tissue regeneration in OP (Stapleton et al., 2017). Bioceramics cover a notable part of biocompatible materials to use in bone fracture or OP treatment (Kankilic et al., 2016). Given the circumstances of ECM role in repair, bioceramics are good alternatives with its increased effectiveness as nano HA forms and combination with zinc, magnesium, silicon and strontium. Mesenchymal stem cells under influence of BMP can develop into osteoprogenitor cells (Kankilic et al., 2016). Nano forms of bioceramics can also be used in fracture healing with MSCs as of their osteoinductive effects (Kankilic et al., 2016).

Osteomyelitis

Acute or chronic osteomyelitis is the inflammation and bacterial infection of bone that may lead to destruction of the tissue. Among many causes of osteomyelitis, mostly seen reasons are contamination during surgery or open fracture and disorganization of circulation and malnutrition. Mostly Staphylococcus aureus is the cause of infection. Osteomyelitis is unfortunately resistant to treatment due to biofilm production (Öztuna, 2005). Although antibiotics are frequently used for treatment, in the literature vancomycin absorbed poly (L-lactic acid) (PLLA)/β-tricalcium phosphate (β-TCP) and quinolone conjugated oligopeptides are reported to decrease bacteremia and limit the infection (Takahashi et al., 2008; Kankilic et al., 2014). Implant related osteomyelitis may need the removal of the implant and for more efficient bone healing vancomycin-containing PLLA/β-TCP composites can be applied (Kankilic et al., 2014).

Osteoarthritis (OA)

Prevalence of OA increases with age although it is influenced by multiple factors (Ross, 2011). Pathophysiology and clinical symptoms are usually progressive degeneration and degradation of joint cartilage tissue and deformity, limitation of movements with pain (Fig. 6.19). Systemic usage of painkillers and cartilage tissue supportive agents might have side effects. So intra-articular hyaluronic acid and glycosaminoglycans are used for local treatment. Not only as being a destructive and progressive cartilage tissue disease, including accompanying peripheral bone tissue and connective damage in time, treatment of OA needs to be improved. Biocompatible polymers have potential to try on cartilage tissue healing in OA. Poly(e-caprolactone), a hydrophobic low degrading material, has been reported to improve bone tissue healing in an OA model when combined with doxycycline and chondroitin sulfate (Aydin et al., 2015).

Osteogenesis imperfecta (OI)

Osteogenesis imperfecta also known as fragile bone tissue disease is mainly a connective tissue disorder. Reduced bone tissue density, increased fracture risk and failure in developing are the natural courses of the disease (Bacon and Crowley, 2018). Osteogenesis imperfecta has 6 subtypes and mostly seen subtype is type 1 OI. Easily broken bones, blue sclera, deafness and developmental failure are clinical findings (Bacon and Crowley, 2018).

Although it is caused by genetic disorder, SOST antibody and TGF-β are experimentally used in treatment. Sclerostin analouge romosozumab is reported to reduce bone tissue degradation and induce new bone formation in humans (Bacon and Crowley, 2018). New agents like romosozumab however need to be proved as biosafe drugs (Bacon and Crowley, 2018).

Conclusion

Bone is a complex natural material which behaves differently under various forces. Current researches are mostly related with the underlying relation between the structure-function and biomechanical behavior of the bone. There are basically five forces applied to bone: compression, tension, shear, bending, torsion or combined of these forces. If the magnitude of these forces exceed the bone's elastic limits, bone, then, gets elastically deformed and microdamages, failures or fractures may occur. However, it is hypothesized that bone remodeling mechanism activates itself against microdamages. So, bone as a composite material, can adapt through modeling and remodeling in order to accommodate loads unless magnitudes of the forces are over the mechanical limits of the bone.

Bone tissue with its cells and matrix form a unity in reply to environmental challenges. Its structure functions to protect internal organs including the brain, the spinal cord, the lungs, the hearth and abdominal organs. Metabolic functions include preserving minerals and production of all blood cells in the marrow. Adaptive behaviors allow human movement by attaining lever arms for tendons of skeletal muscles. Bone cells and ECM play key roles for development, growth and regeneration. Osteocyte signaling regulates turnover of bone. Osteoclast resorption is followed by vascularization and new bone formation by osteoblasts under normal conditions.

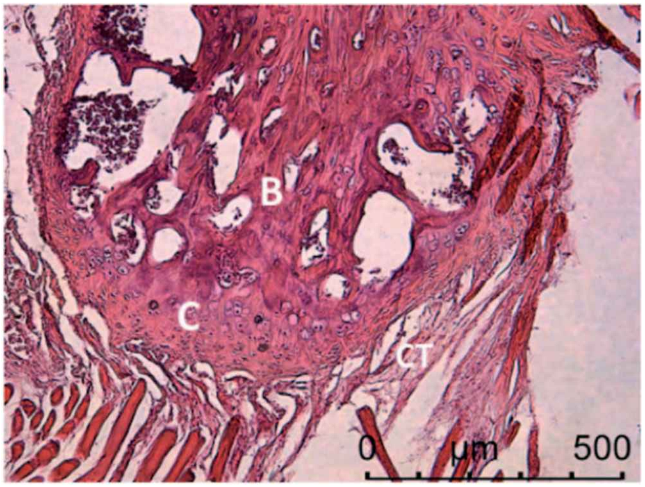

FIGURE 6.19 Articular cartilage (C) damage in osteoarthritis is presented. Bone (B) defect and the connective tissue (CT) are observed on the micrograph (100x, Haematoxylin Eosin).

Allowing that bone preservation is provided by matrix degradation and new bone formation, new research should focus on homeostasis of the tissue. Finally, considering from the beginning of the development of bone tissue cells and signaling pathways for bone formation could be the key points for further experiments.

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Chapter 7

Architecture of cartilage tissue and its adaptation to pathological conditions

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Introduction

Cartilage tissue is a type of connecting tissue and presented in many body areas. It has a major role in supporting the structure and movement of joints. Basically, there are three types of cartilage tissue in human body which are hyaline, elastic and fibrocartilage. Hyaline cartilage is situated on the surface of long bone's joints and enchondral ossification center. Elastic cartilage is found in the structure of ear, auditory canal and larynx. Finally, fibrocartilage is involved in the structure of symphysis pubis and intervertebral discs. In this chapter we focused on hyaline cartilage, which is commonly found in synovial joints.

Hyaline cartilage is a highly specialized tissue found in synovial joints. Its basic function is to provide a smooth, lubricious surface and transfer the load to subchondral bone. Cartilage tissue, which is lack of lymphatic and blood vessels, and does not contain nervous tissue, is exposed to a stiff biomechanical environment. Due to its resistance to axial forces and elastic construction, the force is equally distributed to the subchondral bone and disproportionate loading is prevented. This highly resistant and inert tissue, obtains sustaining flawless joint movement for many years in healthy individuals (Mankin, 1982; Buckwalter and Mankin, 1998; Buckwalter et al., 2005; Brody, 2015).

Articular cartilage has a low repair capacity and self-renewal in case of injury, since it has a limited blood circulation. Severe pain and disability may be encountered by diseases which disrupt the structure or congruity of this tissue (Brody, 2015). Despite the remarkable development in modern surgical techniques and joint arthroplasty, there is no treatment option available which totally recovers the hyaline cartilage functions yet (Fig. 7.1) (Buckwalter et al., 1994a, 2005; Buckwalter, 1998).

Microstructure of the cartilage

Cartilage tissue basically consists of chondrocytes and extracellular matrix. Chondrocytes are highly specialized cells and their function is to synthesize extracellular matrix components and sustain the properties of this matrix. The main components of extracellular matrix are water, collagen and proteoglycans. These basic macromolecules hold the water inside the cartilage tissue and ensure its unique mechanical properties. Non-collagenous proteins, glycoproteins, lipids and phospholipids are also found in cartilage in smaller amounts (Buckwalter and Mankin, 1998).

Mature articular cartilage is 2–4 mm thick. Its thickness, cell distribution, matrix composition and mechanical properties may be differed compared to other zones of cartilage or other joint cartilages (Armstrong et al., 1979). There are four types of layers in accordance to functionality and structure: (1) superficial zone, (2) transitional zone, (3) deep or radial zone and (4) the calcified cartilage zone (see Fig. 7.2) (Clarke, 1971a,b). The shape and distribution of chondrocytes and extracellular matrix components are different in each zone which have diverse functions and properties (Athanasiou et al., 1991). In addition to these layers, extracellular matrix is also divided into three regions according to the relationship with chondrocytes: (1) pericellular matrix, (2) territorial matrix and (3) interterritorial matrix (Clarke, 1971a,b).

Layers

Superficial zone

Is the outermost layer next to joint cavity. This layer protects the deeper layers from tensile and shear forces

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occurring during joint motion and holds them together. It is nearly 0.2–0.5 mm thickness and forms 10–20% of the cartilage. This zone consists of two layers. Lamina splendens is just next to joint cavity and does not contain any cell. It is composed of fine fibrils and polysaccharides. Under this fine layer the main superficial zone is found. Flat chondrocytes lying parallel to the joint surface, high collagen and low proteoglycan ratio is the characteristic features of this zone (Clarke, 1971a,b).

Chondrocyte density is higher in this zone. Also compared to the other zones, the extracellular matrix synthesized by these cells has higher collagen and lower proteoglycan content. Fibronectin and water concentrations are highest in this zone.

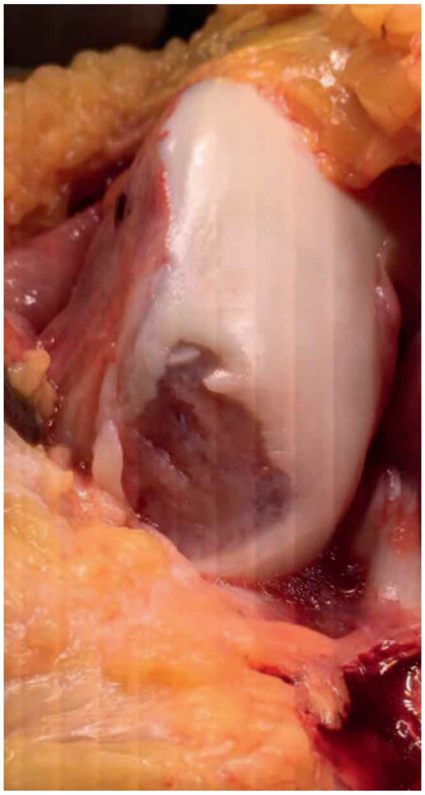

FIGURE 7.1 Osteochondral defect in knee.

Collagen fibers in superficial zone lie parallel to the joint surface just like chondrocytes of this zone (Aspden and Hukins, 1981; Below et al., 2002). This configuration protects the cartilage from tensile and shear stresses. Structural deterioration of this zone, which is in contact with synovial fluid and functions as a mechanical barrier, can cause breakdown of whole tissue. Also, compared to the chondrocytes found in other zones, these cells have lower metabolic rate and potential to repair themselves.

Transitional zone

Transitional zone forms up to 40–60% of the articular cartilage. It is found between superficial and middle zones. In this layer, chondrocytes seem to have spheroidal shape. These cells have higher amounts of endoplasmic reticulum and Golgi membranes, which is interpreted as the metabolic activity of this layer is high. Collagen fibers are thicker in this layer and align in an oblique manner (Aspden and Hukins, 1981; Below et al., 2002). Proteoglycan amount is higher while water and collagen content are low. This zone resists to compressive forces.

Middle zone

Middle zone has the highest resistance to compressive forces, due to its highest proteoglycan concentration and perpendicular arrangement of chondrocytes and collagen fibrils which reach out tidemark to the joint line (Aspden and Hukins, 1981; Below et al., 2002). Chondrocytes assume a spheroidal shape and collagen fibers are thickest in this zone. Also, water concentration is the lowest.

Calcified cartilage zone

Calcified cartilage zone separates cartilage from the subchondral bone. It provides strong attachment of cartilage to subchondral bone. There is a thin layer called tidemark

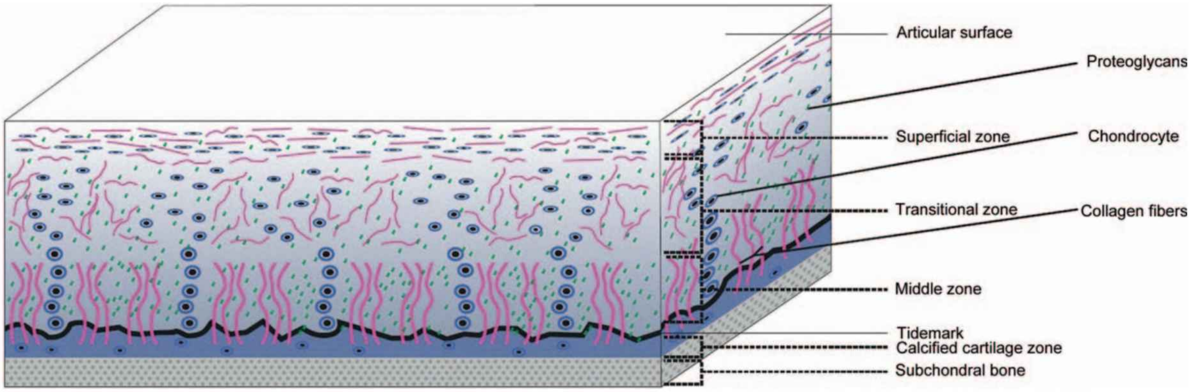

FIGURE 7.2 Chondrocytes and extracellular matrix organization in cartilage tissue.

between deep zone and itself. It functions as a mechanical buffer between non-calcified cartilage and subchondral bone. Chondrocytes are few, hypertrophic and metabolically inactive at this zone (see Fig. 7.2).

Matrix regions

Not only extracellular matrix has different contents and functions due to its zone, but also its contents, properties and functions change due to its proximity to chondrocytes. Extracellular matrix which surrounds the chondrocytes are called pericellular matrix. This matrix is covered with territorial matrix, and rest of the matrix which surrounds all the remaining tissue is called interterritorial matrix. Pericellular matrix and territorial matrix mainly supply the metabolic needs of chondrocytes and provides the mechanical support, while interterritorial matrix represents the biomechanical properties of the cartilage tissue.

Pericellular matrix

Pericellular matrix has a rich proteoglycan content and attached to the cell membranes of chondrocytes. Cell membrane associated molecule anchorin CII and type IV collagen are also found in this region (Pfaffle et al., 1990). Pericellular matrix contents are in contact with chondrocyte membrane receptors and has an important role in signal transduction. Chondrocytes respond to changes in matrix by this way (Eggli et al., 1985; Marcelino and McDevitt, 1995).

Territorial matrix

Territorial matrix surrounds pericellular matrix with its fine collagen fibers and holds the cells together. These fibers cross each other and form basket like constructs for mechanical support of the chondrocytes. The cells are protected from deformation stresses via these basket-like structures (Muir, 1995; Guilak and Mow, 2000). Collagen fibers become thicker and start aligning parallel to each other as it goes through interterritorial matrix as a result it is hard to distinguish these regions from each other.

Interterritorial matrix

Interterritorial matrix has the thickest collagen fibers and makes up most of the articular cartilage. Collagen fibers align vertically as they proceed to deeper zones. Proteoglycans are also commonly found in this region (Mow and Guo, 2002).

Chondrocytes

Chondrocytes are the only specialized cell type found in the cartilage tissue. Their diameters vary in between 7 and 30 μm according to the anatomical layer. These cells form 1–2% of the tissue volume (Alford and Cole, 2005). They are responsible for functional and structural integrity of cartilage. Chondrocytes synthesize extracellular matrix during chondrogenesis and provides matrix turnover in mature cartilage. Extracellular matrix components must be synthesized and organized by chondrocytes, for ensuring the normal cartilage functions (Torzilli et al., 1999).

Chondrocytes' size and shape vary depending on the anatomical layer, but all of them has organelles like endoplasmic retinaculum and Golgi membrane for matrix synthesis. Cytoskeleton of chondrocytes is composed of actin, tubulin and vimentin filaments. In superficial layer filament contents are higher and as proceeding to deep zones, its content decreases (He et al., 2013).

As moving to the deeper zones from superficial zone, cell density is diminished and it is three times lower in deep zone; but cell volume is twice higher in deep zone. Besides, cells which lie parallel to the joint line in a flat shape in the superficial zone, turns into an ellipsoidal shape. In deep zone, chondrocytes form 4–8 cell containing groups and align vertically to the surface. Hypertrophic chondrocytes are found in calcified zone (Stockwell, 1967; Stockwell, 1978).

Extracellular matrix

Extracellular matrix of the articular cartilage is mainly composed of tissue fluid and structural macromolecules. Basic biomechanical properties of cartilage tissue, such as the ability to bear load and frictional resistance, are provided by this matrix. Structural macromolecules are mainly collagen and proteoglycans; also lipids, phospholipids, glycoproteins and non-collagen proteins are found in small amounts.

Tissue fluid

Tissue fluid forms up to 80% of weight of joint cartilage. Gas molecules, small proteins and cations balancing the negative charged proteoglycans are found in this fluid (Linn and Sokoloff, 1965; Lai et al., 1991). Water exists in the tissue fluid within the help of proteoglycans and cations. Water content decreases in deeper zones. Tissue fluid provides metabolites necessary for chondrocytes and lubrication for joint motion (Mow et al., 1984).

Proteoglycans

Proteoglycans are composed of a protein core and one or more glycosaminoglycan chains (Hardingham et al., 1990). Disaccharide chains of these glycosaminoglycans have negative electrical charges. Hyaluronic acid, chondroitin sulfate, keratan sulfate and dermatan sulfate are the examples of glycosaminoglycans found in cartilage tissue. The concentrations and types of these molecules vary according to anatomical region, age, trauma or disease conditions (Stockwell and Scott, 1967; Yoshida and Azuma, 1982). Proteoglycans of articular cartilage are studied under two main groups: (1) lectican family and (2) small proteoglycans.

Lectican family proteoglycans are consisted of aggrecan, versican and cartilage link protein. These constructs maintain biomechanical properties like resistance to stress and load transfer (Ruoslahti, 1996). Aggrecans contain many numbers of keratan and chondroitin sulfate chains. Aggrecans, which fill most of the interfibriller space, account for 90% of proteoglycan mass in cartilage tissue. Aggrecans combine with hyaluronic acid and forms aggregates; that is why they are called aggrecans. This combination is powered with link proteins. Aggregates enable to hold the extensive amounts of negative charges in the tissue. Thus, by the effect of Donnan osmotic pressure, positive charged ions and water are trapped in cartilage tissue. According to this, aggrecans' basic function is resisting to compressive forces by retaining water in its structure (Buckwalter and Rosenberg, 1982; Buckwalter and Rosenberg, 1983; Buckwalter et al., 1994b).

Decorin, biglycan, fibromodulin, asporin, lumican, keratocan and mimecan are examples of non-aggregating proteoglycans. These molecules are smaller than aggrecans and they are not capable of mechanical support. They form connections up the other molecules. Decorin and fibromodulin are attached to collagen type II to strengthen fibril network (Hedbom and Heinegard, 1993). Biglycan is commonly seen in pericellular matrix and interacts with collagen type VI (Roughley and Lee, 1994). Also some of these proteoglycans are responsible for binding growth factors and regulate their function and interact with immune system (Hildebrand et al., 1994).

Collagens

Collagens composes approximately 60% of the dry weight of the articular cartilage. Collagen network provides the main shape and tension resistance of cartilage and protects its integrity and stability (Eyre et al., 2006). Proteoglycans and other non-collagen proteins create the overall framework of extracellular matrix by either attaching to this network or existing between water. Collagen is mainly found as fibril structure in cartilage. Those fibrils are in different thickness and show different orientations in various parts of cartilage. They show a parallel arrangement to the surface of joint in superficial zone, whereas they tend to be thicker and straighter in deeper layers of cartilage.

There are many types of collagen in articular cartilage. Classical fibril forming collagen types for cartilage are II, IX, XI and XVI. Type II collagen is 90–95% of all collagen proteins and also it is the main fibrillar collagen of this tissue. It is responsible for the integrity of cartilage. Especially it has role in resisting to shear and tension type of forces. In the early years of life, type IX and type XI collagen fibrils are found in higher amounts in cartilage whereas they leave their places to type II collagen by time (Eyre et al., 2006).

Collagen type VI is found just around the chondrocytes and helps attachment of the cells to the matrix (Marcelino and McDevitt, 1995). Collagen type X is found only in calcified zone and hypertrophic zone of growth plate. Thus, it is thought to take part in cartilage mineralization (Gannon et al., 1991).

Glycoproteins and other non-collagen proteins

Glycoproteins and other non-collagen proteins are molecules which assist the connections between chondrocytes and matrix components. Anchorin CII is a chondrocyte surface glycoprotein which binds collagen and assists chondrocytes to attach collagen fibril network (Mollenhauer et al., 1984). Chondrocyte oligomeric protein is a unique protein of cartilage tissue and exists in territorial matrix. Fibronectin and tenascin are considered to play role in matrix relations (Hayashi et al., 1996). Thrombospondin, which is also named as cartilage oligomeric matrix protein (COMP), makes connections with matrix proteins, cell receptors, growth factors and complement systems. Thus, it has important roles in structural integrity, differentiation and inflammation (Hedbom et al., 1992).

Mechanical properties of the cartilage

The basic function of hyaline cartilage is generating a smooth joint surface with a very low friction and transferring the forces on the joint to the subchondral bone homogeneously. Cartilage tissue must preserve its integrity and mechanical functions for the life time in healthy individuals. During high-energy activities, 150–200 atm of pressure can occur instantaneously in the articular cartilage, but articular pressure diminishes between 35 and 50 atm during static physiologic stresses (Grodzinsky et al., 2000). Also, the friction coefficient of the tissue is in the range of 0.0005–0.04. The cartilage can maintain its microstructure against such high and variable stresses for life long, due to its flawless mechanical construction. By knowing the mechanical properties of the cartilage tissue; we can understand the reasons of morbidity in joint diseases, stop the progression of disease and develop new treatment methods.

A number of biomechanical terms like tensile, compressive and shear stresses, strain, elastic deformation, plastic deformation, Young modulus and viscoelasticity which were mentioned before, must be kept in mind to understand the mechanical properties of cartilage. Cartilage tissue is viscoelastic and two different mechanisms are responsible for this property (Hayes and Mockros, 1971). Flow dependent mechanism is defined with the relationship between tissue fluid flow and frictional resistance. As the pressure in the tissue rises, frictional resistance increases which will obstruct outflow of tissue fluid. This resistance due to tissue fluid is known as biphasic viscoelastic behavior (Mow et al., 1980, 1984; Simon et al., 1984; Ateshian et al., 1997). Macromolecular motion of collagen-proteoglycan matrix is the cause of viscoelasticity in flow independent mechanism. Resistance of these constructs against compressive forces will rise as the stress rises (Hayes and Bodine, 1978). When a substance responds differently, as the direction of the stress is changed; that matter is called anisotropic. Cartilage is accepted as an anisotropic tissue because of its heterogenic structure (Mow and Guo, 2002).

Compressive, tensile and shear stresses develop on the cartilage tissue during joint motion. Compressive stress occurs during load transfer and it is perpendicular to the joint surface. Tensile stress is formed due to deformation of cartilage laterally, during compressive strains. The shear stresses develop between the two surfaces that slide on each other along with joint motion (Fig. 7.3). The ability of cartilage tissue to withstand these physiological stresses is dependent on extracellular matrix contents and its structural integrity. This integrity is obtained by chondrocytes which responds to biomechanical stresses by synthesis and degradation of matrix molecules. Recent studies showed that, collagen fibers resist to tensile and shear stresses, while proteoglycans resist to compressive stresses and fluid flow. This is the main reason why collagen fibers lie parallel to the joint surface in superficial zone, oblique in transitional zone and perpendicular in deep zone; and proteoglycan concentration increases through the deeper zones of cartilage. During activities such as climbing stairs, 150–200 atm pressure can be instantaneously generated in joint cartilage. These intense stresses result in 1–3% compressive strain due to its short duration. But, when 35 atm pressure is applied for 5–30 minutes, the strain rises up to 35–45% (Herberhold et al., 1999; Grodzinsky et al., 2000).

Theories and the fluid flow

Articular cartilage is a permeable, heterogenic, viscoelastic and anisotropic tissue which is filled with water. Thus, when loaded, cartilage changes its shape, preserves lubricity and provides movement (Woo et al., 1987). The biomechanical properties of hyaline cartilage are understood easily when it is assessed in two phases: the solid phase and the liquid phase. According to this, water and inorganic ions solved in water are the components of the liquid phase. Extracellular matrix components like proteoglycan aggregates and collagen fibers build up the solid phase. The elastic modulus of these two phases differ from each other. Due to biphasic theory, loads on articular cartilage is neutralized with three mechanisms: (1) tensile stress of the solid phase, (2) increased pressure in the liquid phase and (3) frictional resistance during fluid flow (Mow et al., 1984; Ateshian et al., 1997).

Solid phase is a porous, elastic and permeable structure. Permeability decreases in deeper layers of cartilage. Fluid flow requires high hydrodynamic pressure in solid matrix. Permeability determines the resistance to fluid flow. As fluid pressure withstands to compressive stresses; it decreases the stress on solid phase. After dynamic loads on articular cartilage, the shapes of chondrocytes and extracellular matrix change. This deformation increases the fluid pressure, and the pressure gradient

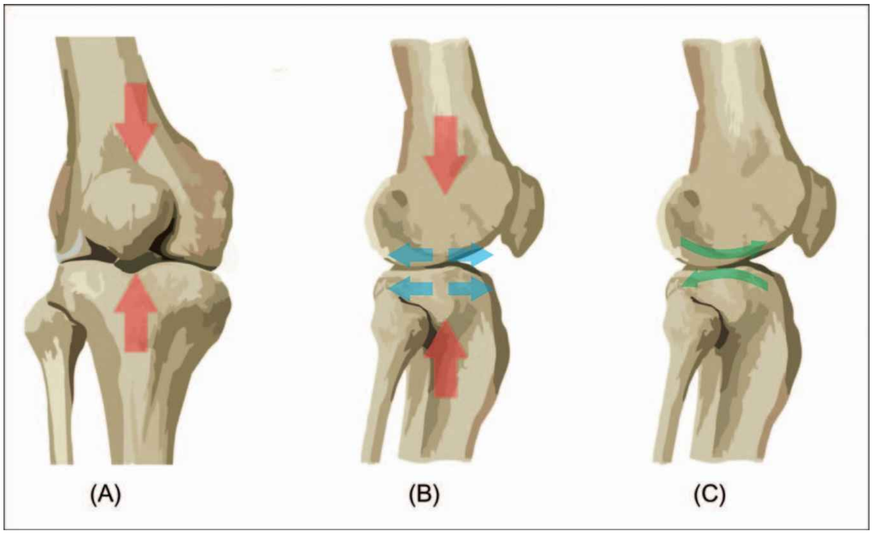

FIGURE 7.3 Mechanical forces around knee joint. (A) Red arrows indicate compressive forces. (B) Blue arrows represents tensile forces. (C) Green arrows symbolize shear forces.

induces fluid flow outside to extracellular matrix (Maroudas and Bullough, 1968; Mow et al., 1984; Frank and Grodzinsky, 1987). As the stress is removed fluid turns back to cartilage tissue. Frictional resistance against this flow through the matrix is very high; so, the permeability of the tissue is very low. Limited permeability of articular cartilage prevents all of the fluid flow outside the tissue (Mow et al., 1984, 1992).

Compressive stiffness of articular cartilage is provided by its proteoglycan content. Due to negative repulsive electric forces between proteoglycan aggregates and tissue fluid, cartilage resists to compressive stresses. As the fluid content increases, the tissue softens and its permeability rises (Maroudas et al., 1991). Proteoglycan aggregates found in cartilage contains dense negative charge. This solved negative electric charge pulls water and positive ions itself to be neutralized. Concentration of ions in the cartilage is always higher than its outer area and this imbalance will increase the pressure in interstitial fluid (Myers et al., 1984). This osmotic pressure is also called Donnan osmotic pressure (Buckwalter and Mankin, 1998). So, in addition to biphasic theory; recent studies showed that this osmotic pressure has an important role in resisting to compressive forces; because of negative electrostatic repulsion forces, ions' diffusion, interstitial fluid pressure due to osmotic effect and chemical expansion in solid matrix. Thus, ions in tissue fluid are defined as the third phase; and the triphasic theory is introduced (Lai et al., 1991).

When a compressive force is applied to cartilage tissue, not only it deforms vertically but also laterally and it is called Poisson ratio effect. Because of its position between bone and cartilage, this shear stress is highest in tidemark. Shear resistance is provided by its collagen and proteoglycan structure. In cartilage under Paisson ratio effect, there will also be a tensile stress and this is resisted by collagen fibers.

Lubrication between the articular surfaces is essential for sustaining motion. There are two basic mechanisms for obtaining joint lubrication. First mechanism is weeping lubrication, due to which fluid outflow provides an elastohydrodynamic lubrication during load bearing. On the other side, according to surface lubrication; hyaluronic acid, lubricin, lipids and other hydrophilic molecules which are found on the articular surface ensure lubrication (Jay et al., 2001). These two mechanisms work together, but weeping lubrication has more a more important role in fast movements; while surface lubrication mechanism takes more part in static loading.

In experimental studies, it has been understood that joint loading can cause different metabolic responses in the cartilage tissue. Immobility or lower activity rates are shown to reduce matrix synthesis and soften the cartilage tissue. On the other hand, proteoglycan concentration is found to be higher in load bearing joints and as load bearing increases in physiologic limits, this concentration could be raised. Also, cartilage degradation is induced after heavy exercise and higher stresses. Similarly, exposing to heavy loads for a long time stimulates cartilage tissue degeneration. Constant compressive forces are shown to reduce matrix synthesis, while cyclic loading induce synthesis in vitro studies (Buckwalter and Grodzinsky, 1999; Urban, 2000).

Cartilage tissue in different life stages

Significant changes are seen in older ages in hyaline cartilage. The most prominent structural change is fibrillation of the joint surface; but this does not cause pain or joint dysfunction. This is thought one of the a natural sign of aging. Chondrocytes get bigger; but the decrease in their number is relatively higher and this causes a lower cell ratio in time. Permeability, water and proteoglycan content also gets lower. Due to these changes tissue gets harder and loses its elasticity (Buckwalter et al., 1993).

Cartilage tissue is isotropic and has higher cellular content at birth. Over time it is divided into specific layers, gains different structural properties and become anisotropic. It also takes part in growth plate structure and aids lengthening of the long bones. After adolescence cartilage tissue sustains its load transfer and joint motion functions.

There is a single type of cell called chondrocytes in the cartilage tissue. They are responsible for cartilage synthesis called chondrogenesis. During chondrogenesis mesenchymal stem cells turn into chondrogenic progenitor cells and these cells differentiate to chondrocytes. These are chondrocytes' function to synthesize extracellular matrix during chondrogenesis and to provide matrix turnover in whole life. Chondrocyte volume increases, telomere length and mitotic activities decrease within time and these changes are called state of senescence. Shortened telomere length is caused by repeated replications. Also, overloading chronically or trauma results in proliferation of chondrocytes and shortening of telomere length (Martin and Buckwalter, 2001a,b). Mechanical loads raise oxidative stress and induces apoptosis. Thus, chondrocyte number decreases within age. In elder ages, changes in the chondrocyte functional capacity lead to reduce the renewing and healing potential of the cartilage tissue (Guerne et al., 1995). Not only chondrocyte functions reduce within age, but also its proteoglycan synthesis capacity, proliferation potential and responses to anabolic stimulants diminish too (Martin et al., 1997). As a result, elder people are susceptible to degenerative arthritis (Martin and Buckwalter, 2001a,b).

Collagen amount and content of extracellular matrix change within time, too. In childhood, the ratio of type II collagen is less than 80% while the ratios of type IX and XI collagen are higher than 10%. These ratios change in adulthood and becomes higher than 90% for type II collagen and lower than 1–3% for type IX and XI collagen (Eyre, 2002). Type IV collagen amount also increases with aging. Collagen fibers become stiffer in time and this is caused by non-enzymatic cross link formation. Advanced glycation end products are responsible for this link formation (Roth and Mow, 1980). Collagen turnover is seen in only first 20 years of life. In conclusion to these changes, the resistance of cartilage tissue to tensile stress is diminished in time.

The amount of proteoglycan aggregates is lower as a result of aging. The reason of this change is becoming smaller of aggregates due to shortening of the chondroitin sulfate chains. In vitro studies showed that old chondrocytes synthesize smaller and less organized proteoglycans in tissue. Also, chondroitin 4 sulfate amount decreases, while chondroitin 6 sulfate amount does not change and keratan sulfate amount raises. Such changes in proteoglycan turnover results in regression of biomechanical properties of cartilage (Hardingham and Bayliss, 1990).

Adaptation of the cartilage to pathological conditions

Cartilage, which has a limited capacity of self-renewal, must preserve its structural integrity to maintain its biomechanical functions. Pathological changes in structure of cartilage may cause tissue loss, pain, diminished range of motion and disability (Buckwalter, 1998). Most common cartilage disease is degenerative arthritis and primary osteoarthritis is the most common form. Trauma, infection, metabolic and genetic diseases can cause secondary osteoarthritis.

Degenerative arthritis is characterized by sclerosis and remodeling of subchondral bone, loss of articular cartilage, subchondral bone cysts and marginal osteophyte formation. Pain, limited motion, swelling, crepitus and deformities are the common clinical features of this disease. It can affect any synovial joint and its earliest microscopic finding is fibrillation of the superficial zone through the deeper zones (Reimann et al., 1977; Poole et al., 1993; Oddis, 1996).

The relationship between cartilage loss and subchondral sclerosis is controversial. Some authors postulated that increased stress due to the loss of cartilage induced subchondral sclerosis; while the others think that hardening of subchondral bone because of subchondral sclerosis is the reason for cartilage loss. It is not clear that which of these theories are right yet; but it is obvious that in symptomatic patient cartilage loss and subchondral sclerosis is seen together (Radin and Rose, 1986). As the disease progress, fibrillations found on the surface proceed to subchondral bone and results in loss of thickness of cartilage. The disease has three basic stages. In first stage extracellular matrix damage occurs. Then, in the second stage, chondrocytes respond to damage. This respond decreases in time. In the third stage progressive tissue loss is seen (Ehrlich et al., 1987; Martel-Pelletier et al., 1994; Testa et al., 1994).

Proteoglycan loss and water amount increase is noted in the first stage of degenerative arthritis. Collagen type IV amount increase, while type II collagen ratio does not change. Changes in fibril network, lower aggrecan concentration, shortened glycosaminoglycan chain length and increased water amount, enhances matrix permeability. This enhanced matrix permeability softens the cartilage tissue and makes it more vulnerable to mechanical damage (Mankin, 1974a,b). These changes might be triggered by obesity, trauma, metabolic or inflammatory diseases (Maeda et al., 2005; Desrochers et al., 2010; Herz et al., 2014; Reina et al., 2016). Chondrocytes detect these changes, proliferate and increases its anabolic and catabolic activities. Growth factors induce proteoglycan and collagen synthesis, and at the same time pro-inflammatory cytokines release many protease enzymes. At this stage of osteoarthritis, if the anabolic response of chondrocytes dominates the catabolic response, the disease does not progress; even healing may occur. In case of the situation which chondrocytes cannot provide sufficient anabolic response and protease enzymes spread through the matrix; matrix degradation accelerates and the disease progresses. Loss of proliferative and anabolic properties of chondrocytes within time is one of the main reasons why this disease is commonly seen elder people (Mankin et al., 1981; Cs-Szabo et al., 1995).

Progressive cartilage loss become obvious in the final stage of osteoarthritis. Subchondral sclerosis, remodeling and cysts are noted (Fig. 7.4). Marginal osteophytes are typically found around bone and joint interface; and they are thought to develop in response to the anabolic cytokines affecting bone and cartilage (Varich et al., 1993; van Beuningen et al., 1994; Aigner et al., 1995; Middleton et al., 1995).

Secondary osteoarthritis can be caused by many diseases. Proteoglycan fragments and protease enzymes are found to be higher in joint fluid for a very long time after joint trauma. Also, apoptosis due to trauma and matrix degradation is a risk factor for developing posttraumatic degenerative arthritis (D'Lima et al., 2001; Fukui et al., 2001; Patwari et al., 2001; Desrochers et al., 2010). Incongruity and improper friction in dysplastic joints might also induce degenerative arthritis. Subchondral bone loss and collapse of the cartilage in aseptic necrosis is another important cause of secondary osteoarthritis. Intraarticular bleeding in hemophilia and homogentisic

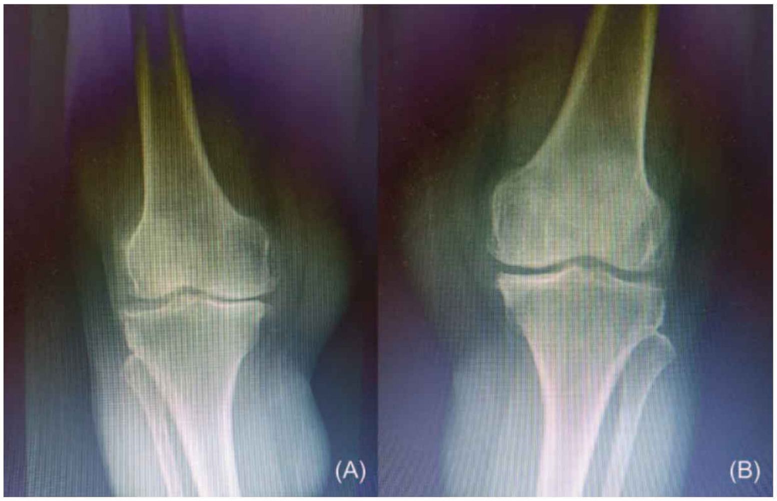

FIGURE 7.4 Radiographic views of stage III (B) and endstage (A) osteoarthritic knee.

acid deposition in case of ochronosis induces inflammatory response and matrix degradation. Also, loss of cartilage tissue after septic arthritis and proprioception loss due to peripheral neuropathy are other common causes of secondary osteoarthritis.

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Chapter 8

Architecture of muscle tissue and its adaptation to pathological conditions

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Introduction

Comprehension of structure-function relationship of skeletal muscle provides better understanding of the properties of different muscles. Macroscopic arrangement of the skeletal muscle is called muscle architecture (Lieber and Friden, 2000). This definition not only explains the force production and function, but also gives insight to a basis for injury mechanisms, loading rules, planning of tendon transfers, determining stretching and strengthening regimes and creating specific approaches in the pathological conditions (Lieber, 2002a,b,c). Muscle architecture is primary determinant of muscle function and it's highly adaptive according to the loading. Sarcomere structure and fiber type distribution are generally emphasized to explain muscle function and adaptation. However macroscopic arrangement of the fibers and their geometry are mainly responsible for specific muscle function (Lieber and Friden, 2000; Lieber and Ward, 2011; Frontera and Ochala, 2015). Even though there is an obvious improvement in the imaging techniques, analysis and interpretation of the muscle fiber arrangement has received much less attention. Generally, muscle specific exercise programs are planned based on fiber type distribution of each muscle. However, fiber type distribution can be different between individuals even for the same muscle. Also, fiber type distribution is influenced by systemic factors (Campbell et al., 2013; de Rezende Pinto et al., 2015; Frontera and Ochala, 2015; Walther et al., 2015). For these reasons muscle architecture-based exercise or loading should be considered in all movement restorative processes.

Muscle architecture is defined as the arrangement of muscle fibers relative to the axis of force generation (Lieber and Friden, 2000; Lieber, 2002a,b,c). Arrangement of the fibers is various between muscles. Moreover, different parts of same muscle such as quadriceps femoris can display difference. In addition to the fiber arrangement, sarcomere length is another important parameter for the muscle function (Lieber and Friden, 2000; Lieber, 2002a,b,c; Lieber and Ward, 2011; Lieber et al., 2017). These features should be considered together for planning rehabilitation including but not limited to tendon transfers, orthotic devices, neuromuscular electrical stimulation applications and stretching programs. Beyond this basis, muscle architecture-based planning in rehabilitation may have advantage to develop evidence based and novel treatment techniques. It can be helpful to determine treatment approaches in specific conditions such as spasticity. It can also provide links between pathologic conditions and muscle adaptations that are not yet resolved in the literature. The purpose of this chapter is to describe the significance of muscle architecture and to introduce specific concepts in rehabilitation of skeletal muscle.

Microstructure of the muscle tissue

Muscle fibers consist of myoblasts. Each fiber length is consistent in size within a muscle. The sarcoplasm is defined as cytoplasm of each fiber and it's surrounded by sarcolemma. Contractile segment is located in bulk of sarcoplasm and organized in myofibrils with 1−2 μm diameters through all fiber length. Fibers, on the other hand, have diameters ranging from 10 μm to 100 μm. Nuclei are found between myofibrils and sarcolemma. In transvers section of a muscle fiber only a few nuclei can be seen while several hundred can be seen in entire length of the fiber (Lieber, 2002a,b,c; de Rezende Pinto et al., 2015; Frontera and Ochala, 2015). This arrangement is highly specialized to produce movement and force. Herein,

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muscle fiber is very important since its diameter is determinant of the strength and its adaptation means the changing of its usage. Length of fiber is variable and its length meanly affects the architecture. It influences the contraction velocity.

Basal lamina is one of the important parts of the muscle. It is crucial for recovery of muscle after injury. If the basal lamina remains intact even in case of severe fiber injury, almost full recovery is expected. It envelops myotubes together during development of the muscle. Also, it expresses various proteins to keep intact the fiber function (Lieber, 2002a,b,c; de Rezende Pinto et al., 2015; Frontera and Ochala, 2015).

Connective tissue layers of the muscle have an important role together with the giant protein called "titin". Each fiber is surrounded by a loose connective tissue called "endomysium". Electron microscope scanning showed an intimate interaction between endomysium and the muscle fiber. The connective tissue matrix within the endomysium provides not only a supporting role, but also transmission of forces from muscle to tendon. The fascicles are surrounded by a stronger layer called perimysium. Finally, whole muscle is enclosed by epimysium. These connective tissues are highly adaptive as muscles in muscle injury, loading and denervation. Their connective tissue quantity and thickness can be changed depending on the conditions and they can alter the muscle tone, elasticity and strength. The connective tissue layers of the muscle compose the non-contractile part of the muscle (Lieber, 2002a,b,c; Frontera and Ochala, 2015).

Contractile parts of the muscle are consisted of myofilaments, myofibrils and fibers, hierarchically. Myofibril is the largest functional unit. Sarcomeres are arranged in myofibrils. Thousands of myofibrils generate a single muscle fiber. Although their parallel arrangement is generally known as a bundle consisted of straight lines, in fact their arrangement is wavy. Myofibrils are interconnected to another by intermediate filament network such as desmin. This network plays an important role in adopting the muscle to the mechanical stresses within the rules of mechanotransduction (Lieber, 2002a,b,c; Frontera and Ochala, 2015) (Fig. 8.1).

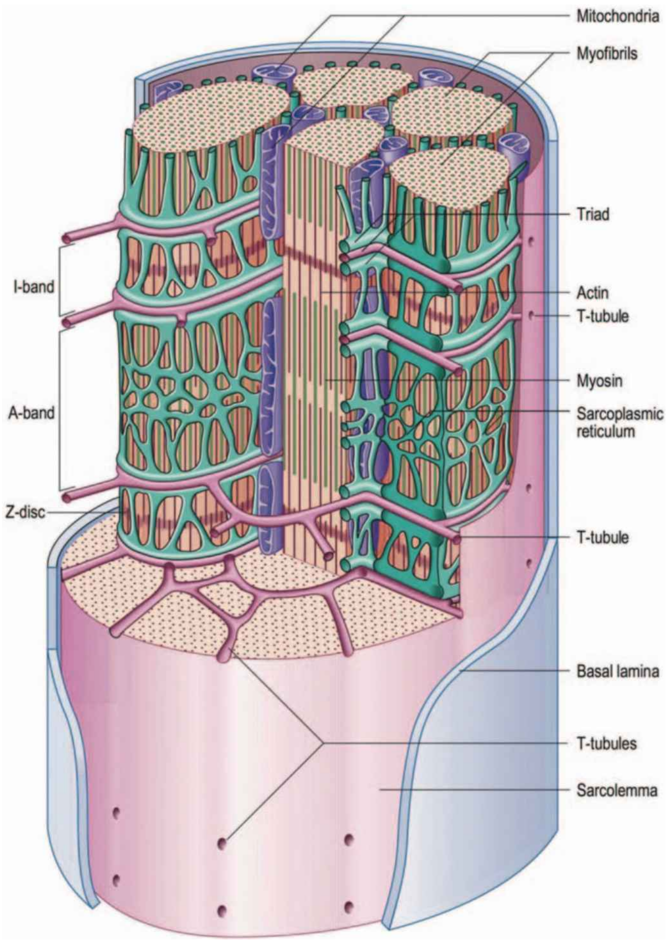

FIGURE 8.1 Hierarchical structure of the muscle including connective tissue layers (Standring, 2016).

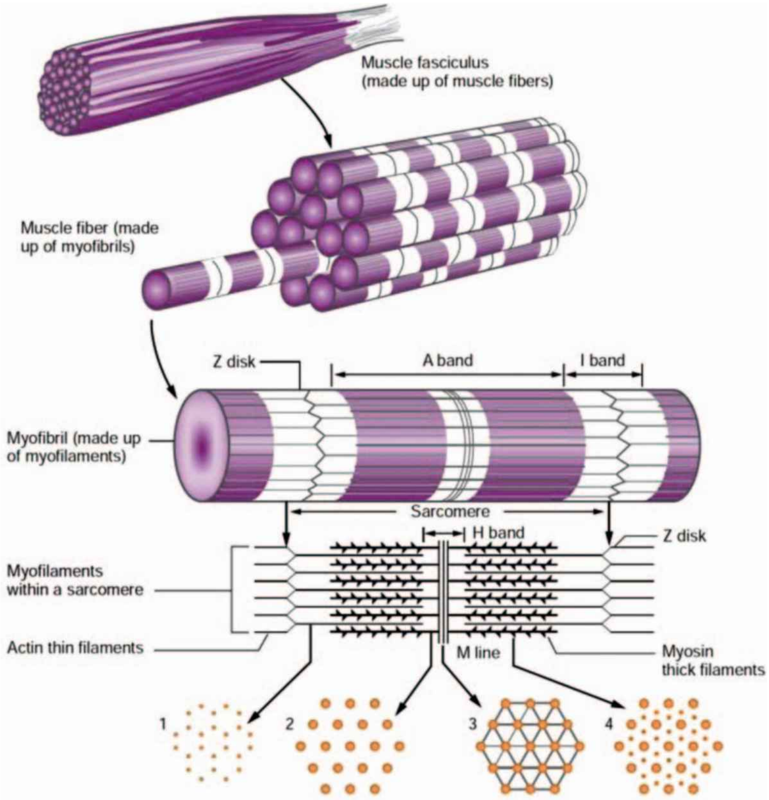

FIGURE 8.2 Sarcomere structure. Arrangements of thin and thick filaments are seen (Goodman, 2008).

A myofibril is formed with the serial arrangement of sarcomeres and their number depends on the fiber length of the muscle. Sarcomeres are composed of myofilaments (Fig. 8.2). Each sarcomere contains thin filaments (5 nm diameter, actin protein), thick filaments (15 nm diameter, myosin protein), elastic filaments (titin) and inelastic filaments (nebulin and titin). Actin and myosin are contractile parts whereas titin and nebulin are non-contractile parts which act as an intramyofibillar cytoskeleton (Lieber, 2002a,b,c; Frontera and Ochala, 2015; Narici et al., 2016). Interlocking of the thick and the thin filaments is seen as a striated appearance in light microscope. Therefore the term of striated muscle is defined due to the light and dark banding pattern. Actin is the major component of the thin filament. It has a double helix which spiraling each other. Troponin and tropomyosin are also important proteins since they regulate making and breaking connections between actin and myosin during contraction and relaxing (de Rezende Pinto et al., 2015; Frontera and Ochala, 2015).

Regions of sarcomere are defined with respect to the light and light appearance. Myosin region is known as the A-band while actin region is known as the I-band. A-band contains the H-zone which there is no actin-myosin overlap. The line that bisects the I-band and limits the sarcomere is called as Z-band. Last band is known as M-band which located in the center of A-band (Fig. 8.3). Since sarcomere length is an important determinant of the muscle function, Z-band is highly important (Lieber, 2002a,b,c; de Rezende Pinto et al., 2015; Frontera and Ochala 2015). Central position of the A-band is provided by titin which links to the Z-line. Titin is one of the largest protein structures in the sarcomere. It spans from Z-line to M-line. Due to its elastic structure it acts like a spring and resists to stretching and keeps the sarcomere length. It also plays a key role during eccentric loading (Lieber, 2002a,b,c; de Rezende Pinto et al., 2015; Frontera and Ochala, 2015).

Myosin is the main area where cross-bridges exist. Myosin proteins with a tail-to-tail arrangement form the myosin filament. Between the each tail there is 1.46 nm distance and 60° rotation. These tails located in peripheral parts of the myosin fibril and the center of the myosin has a tail-free region named as H-zone. Thus, myosin can attach to the actin to generate the cross bridges. The A-band is formed by this attachment and overlapping (Frontera and Ochala 2015).

The actin filament is consisted of a long α-helical arrangement of actin monomers. Different from myosin component, it does not have a symmetrical direction to the helix. Actin monomers that have spherical shape are smaller than myosin monomers. Actin containing filament regulates tension generation while myosin generates tension (Lieber, 2002a,b,c; Frontera and Ochala, 2015).

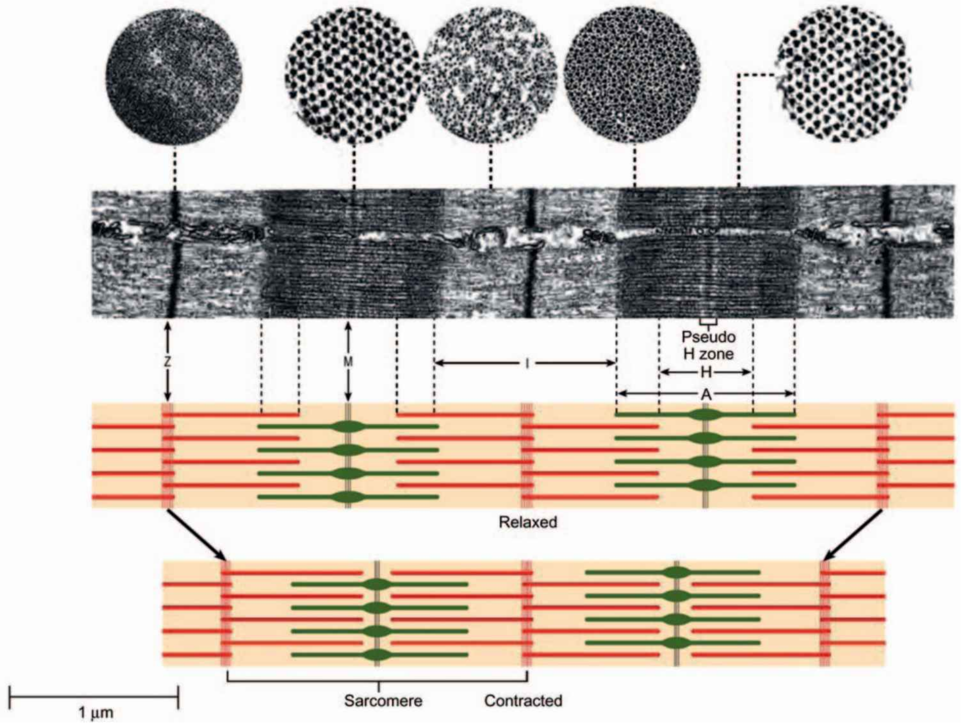

FIGURE 8.3 Darker and lighter bands of the sarcomere (Standring, 2016).

Desmin is a muscle specific intermediate protein. It is expressed by skeletal muscle to provide a frame for muscle cell development. Desmin connects to the Z-discs and creates a cellular skeleton. Titin is also an intermediate protein but unlike desmin it is an inner structural part of the sarcomere (Frontera and Ochala, 2015; Hnia et al., 2015).

Satellite cells are less emphasized components of skeletal muscle. They are located beneath the basal lamina, outside the muscle cell. Its main role is to provide recovery after injury. They have ability to differentiate to myoblasts as stem cell. Thus, nearly complete recovery can be possible in muscle tissue (Lieber, 2002a,b,c; Dumont et al., 2015).

Basic architectural definitions

Muscle fiber length and direction are important parameters to make a functional classification. Fibers which extend parallel to the muscle force-generating axis are defined parallel or longitudinally arranged fibers. Although their parallel settlement, fibers don't extend whole muscle length. These muscles with long fiber lengths generally have long excursion and fast contraction ability. The ratio of muscle fiber length to muscle length ranges between 0.2 and 0.6. This means that muscle fiber length can extend up to 60% of muscle length. Unipennate muscles have fibers that are oriented at a single angle to the force-generating axis which can vary from 0° to 30°. Their force generating ability is higher than parallel oriented muscles. Muscles with fibers that oriented at several angles relative to the force generation axis are named multipennate muscles. This functional classification is basic for architecture based on muscle function and it describes the muscle design basically (Fig. 8.4). It describes a different muscle function beyond the anatomical origin-insertion direction. Thus, function of the separate muscles in same body part, such as thigh or leg, can be understood more clearly (Lieber and Friden, 2000; Lieber, 2002a,b,c; Lieber and Ward, 2011; Frontera and Ochala, 2015).

The general parameters that used in architectural analysis are muscle length (Lm), fiber length (Lf), pennation angle (PA) and physiological cross sectional area (PCSA). Lm is defined as the distance between the most proximal and most distal fibers. Fibers' direction relative to the force-generating axis is named as pennation angle. Although it's an effective method to describe muscle architecture, it may not reflect the muscle function. Because of fibers significantly rotate during contraction, pennation angle changes. Therefore resting and contracted muscle angle values may be different. Ultrasound imaging, which is the easiest way to measure the pennation angle, is generally performed in resting position for a muscle. However alterations during voluntary contraction may not be shown accurately. Nevertheless it is accepted

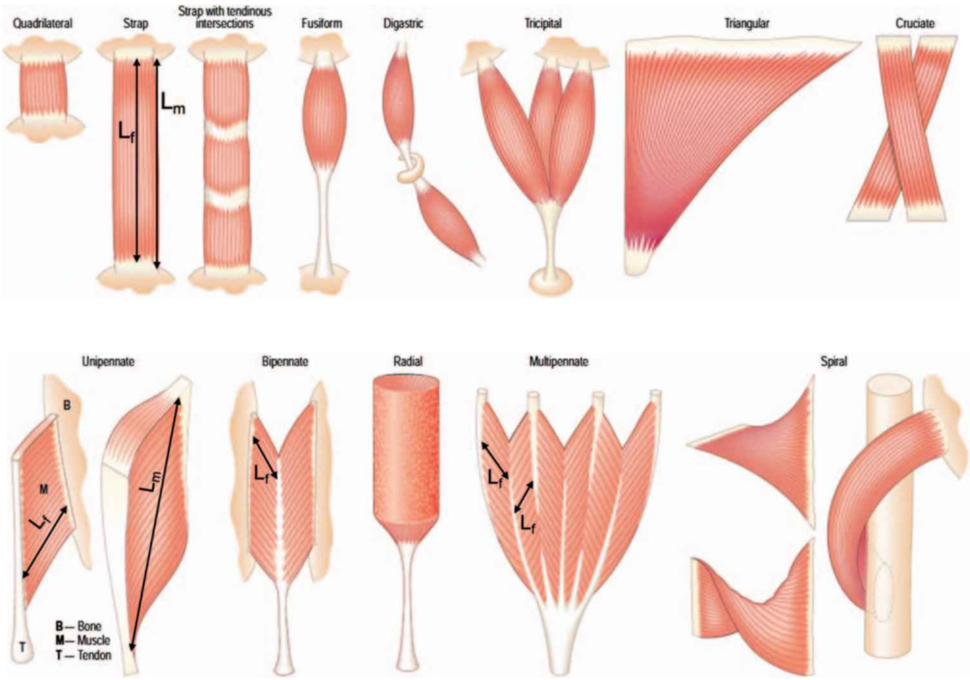

FIGURE 8.4 Morphological types of muscle based on their general form and fascicular architecture (Standring, 2016).

that increase of PA occurs with muscle strengthening. Moreover, stretching decreases PA (Lieber and Friden, 2000; Lieber, 2002a,b,c; Lieber and Ward, 2011; Frontera and Ochala, 2015).

PCSA is directly proportional to the maximum tetanic tension. It does not reflect actual cross sectional area perfectly. It is the sum of the cross-sectional areas of all the muscle fibers and it is influenced by pennation angle. It is calculated using the equation below (Lieber and Friden 2000).

$$\mathrm{PCSA}\left(\mathrm{cm}^2\right) = \frac{musclemass(gram) \times cosinePennationAngle}{muscledensity\left(\frac{g}{cm3}\right) \times Lf}$$

Mechanical properties of the muscle

Length-tension relationship is an important parameter to explore mechanical properties of the skeletal muscle. It's defined as tension values of maximally stimulated skeletal muscles in different lengths during isometric contraction. It can be explained by two mechanisms: active and passive length-tension relationships. The active length-tension relationship reflects the degree of overlap between actin and myosin. Too much and too little degrees generate suboptimal tensions whereas maximal tension is seen in median sarcomere length values. Passive length-tension relationship reflects the presence of elastic elements within a sarcomere, which stretch and produce force with increasing length. Length-tension relationship represents that tension generation in skeletal muscle is a direct function of actin-myosin overlap (Lieber and Friden, 2000, 2002; Lieber, 2002a,b,c; Frontera and Ochala, 2015).

In fact this definition can be expressed as sarcomere-tension relationship. Although Sir Andrew Huxley offered this physiological invention with using an isometric contraction set up, it is accepted for all force producing muscle activities. Knowledge of anatomic lengths of actin and myosin filaments has important implications on understanding normal movement and treatment strategies including tendon transfers, stretching and exercise approaches. Altering the length-tension relationship can have a profound influence on human movements (Lieber and Friden, 2000; Lieber, 2002a,b,c; Frontera and Ochala, 2015).

Length-tension relationship curves are quite different between single fiber and the whole muscle. Analysis of single fiber revealed a sharp shaped curve while analysis of whole muscle revealed more smooth shape due to contribution of muscle, tendon and joints. However both curves show that at short sarcomere and muscle lengths force generation is lower. Also, at long sarcomere and muscle lengths force generation is lower. Therefore the term of 'mid-range' have great importance for achieving optimal muscle performance (Lieber and Friden, 2000; Lieber, 2002a,b,c; Frontera and Ochala, 2015).

Optimal sarcomere length for better muscle function is accepted as 2.6 μm (Fig. 8.5). When the muscle fiber is highly stretched the sarcomere reaches the length of 3.65 μm. The myosin filament is 1.65 μm long and the actin filament is 2.0 μm long and there is no actin-myosin overlap (Fig. 8.6). Thus, muscle cannot generate power. If the

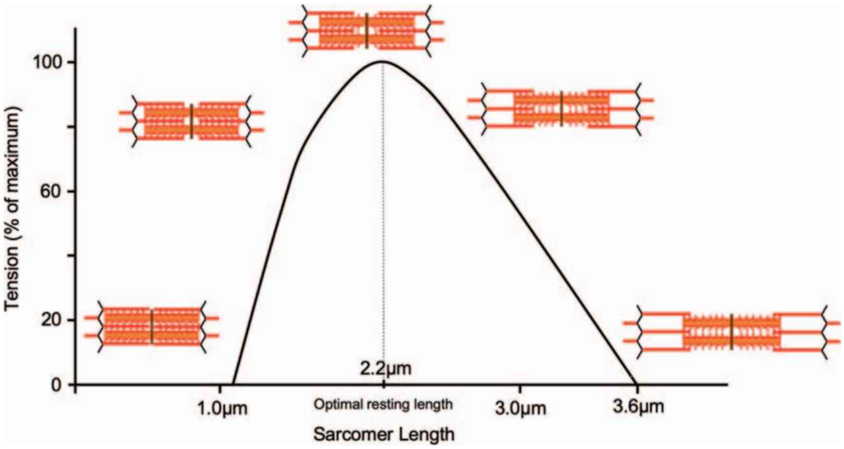

FIGURE 8.5 Maximum force is exerted by a muscle at 2.6 μm of sarcomer length.

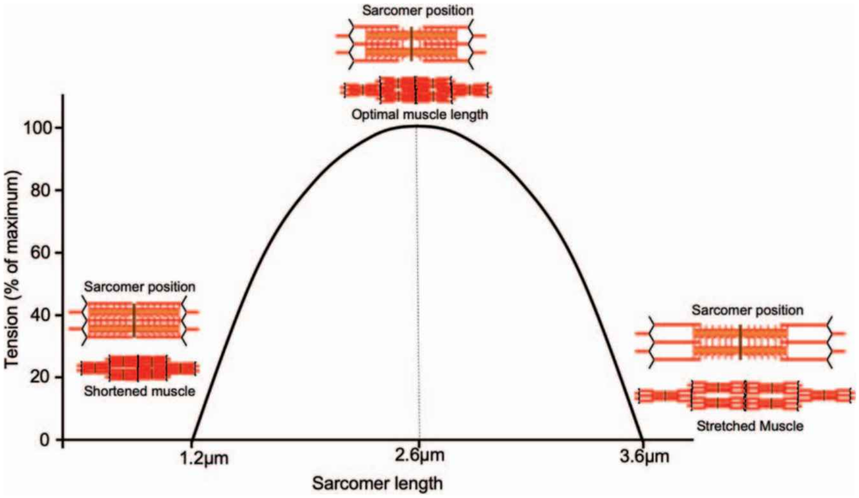

FIGURE 8.6 Alterations in sarcomere length cause alteration in force production.

muscle shortens, actin-myosin interdigitation begins as sarcomere length decreases. Power generation increases until the sarcomere length decreases to 2.2 μm (Lieber and Friden, 2000; Lieber, 2002a,b,c; Lieber and Ward, 2011).

Between 2.0–2.2 μm, muscle force remains constant. If the sarcomere length continues to decrease, it doesn't produce further force since no additional cross bridge connections are made. There are many studies show effect of eccentric exercise on optimal length of the muscle. Optimum length of the muscle was shown improved after eccentric loading. However these studies do not investigate the alterations in sarcomere (Lieber, 2002a,b,c; Lieber and Ward, 2011; Lieber et al., 2017).

Muscles of the upper limb

Upper extremity muscles show an excellent architectural organization due to hand supporting function. Scatter graph of the fiber length and PCSA of upper limb muscles show a homogeneous distribution in contrast with lower limb muscles. Upper extremity muscles have relatively long fiber lengths to meet the need of fast contraction. Triceps brachii seems to be the strongest while long head of biceps brachii seems to be the fastest muscle in arm. In order to plan treatment methods, including tendon transfers, this scatter graph features of muscles can be used Using with this scatter graph features of each muscle can be estimated for planning the treatment methods including tendon transfers (Lieber and Friden, 2000; Lieber, 2002a, b,c; Lieber and Ward, 2011).

Muscles of the lower limb

Lower extremity muscles have relatively short fiber lengths and moderate PCSA values. They generally generate force with small excursions. Sartorious seems to be the fastest muscle whereas the soleus is the strongest according to the scatter graph of lower limb muscles.

TABLE 8.1 Architectural features of the rotator cuff muscles (Ward et al., 2006).

Muscle	Mass (gram)	Lf/Lm	Sarcomere length	Sarcomere number	Pennation angle (°)	PCSA (cm^2)
Supraspinatus	34.0 ± 4.3	0.53 ± 0.03	3.23 ± 0.05	16,665 ± 1182	5.1 ± 0.8	6.65 ± 0.56
Infraspinatus	78.0 ± 7.5	0.55 ± 0.02	3.18 ± 0.05	24,332 ± 1203	1.4 ± 0.4	10.71 ± 0.95
Teres minor	21.2 ± 2.0	0.57 ± 0.03	2.80 ± 0.07	22,569 ± 1299	0.6 ± 0.3	3.13 ± 0.30
Subscapularis	101.8 ± 11.5	0.45 ± 0.02	2.52 ± 0.09	22,069 ± 1735	0 ± 0	15.53 ± 1.41

Lf/Lm = fiber length/muscle length ratio, PCSA = physiological cross sectional area.

Different from upper limb, there are certain differences between agonist and antagonist muscles. While quadriceps femoris have large PCSA and short fibers, hamstring muscles have relatively moderate PCSA and higher fiber lengths. Likewise plantarflexors and dorsiflexors show similar differences (Lieber and Friden, 2000; Lieber, 2002a,b,c; Lieber and Ward, 2011).

Muscles of the shoulder

Subscapularis seems to be the strongest muscle with its higher PCSA when scatter graph of the shoulder muscles were analyzed. On the other hand supraspinatus, which is the most injured muscle, has moderate fiber length and PCSA. In order to explain its vulnerability to injury, parameters such as sarcomere length and pennation angle should be taken into consideration. Supraspinatus has the longest sarcomere length and highest pennation angle within all rotator cuff muscles (Table 8.1). Probably, rotational vigorous contraction in the stretched sarcomere may result with excessive loading in tendon which leads to injury (Ward et al., 2006; Firat and Turker, 2012).

Muscles of the trunk

Trunk muscles support spinal stability and create a core that provides a base for extremity movements. Paraspinal muscles and trunk muscles act together for stability and function. Even though many parameters have been defined, this knowledge is not yet implemented to treatments. When erector spinae muscles were analyzed spinalis thoracis, longissimus thoracis and iliocostalis lumborum showed lower sarcomere lengths (2.26 μm, 2.31 μm and 2.37 μm respectively), relatively higher pennation angles (16°, 12.6° and 13.8°, respectively), lower PCSA values (1.6 cm^2, 5.9 cm^2 and 4.1 cm^2, respectively) and lower Lf/Lm ratios (0.29, 0.28 and 0.36, respectively) (Delp et al., 2001). With these parameters, these muscles have force-generating ability in small ranges. Thus we can assume that they should be re-educated in small ranges to support stability. Also, multifidus has a great stability function with its highest pennation angle (18.4°), shortest fiber length (4.8 cm), huge PCSA (23.9 cm^2) and shortest sarcomere length (2.26 μm) (Vasavada et al., 2011).

On the other hand, rectus abdominis seems to be responsible of motion than stability with its higher Lf/Lm ratio (0.82), lower PCSA (2.6 cm^2), zero pennation angle and higher sarcomere length than optimal (2.83 μm) (Delp et al., 2001).

Another study that analyzed the human abdominal wall muscles showed tremendous information. Rectus abdominis has the highest sarcomere length (3.29 μm) and highest fascicle length as mentioned in previous study. However, transversus abdominis has shorter sarcomere length (2.58 μm) and relatively shorter fascicle length. When we compare these data, we can assume that transversus abdominis is mainly responsible for stability in abdominal wall. This knowledge can explain its importance in core stabilization. It may provide spinal stability especially during trunk flexion and extension since sarcomere length alteration is very limited. But during axial rotation this variance is highest. According to the study, internal oblique muscle is strongest with its highest PCSA values in abdominal wall. It's nearly in optimal sarcomere length (2.61 μm) which is in support of this opinion (Brown et al., 2011).

Muscles of the pelvic floor

A few study give limited information on pelvic floor muscle architecture. Tuttle at al revealed that coccygeus (2.05 μm), iliococcygeus (2.02 μm) and pubovisceralis (2.07 μm) muscles have very short sarcomere lengths. Pubovisceralis have longest fiber length while coccygeus have shortest (Tuttle et al., 2014). In the study of Alperin et al, pubovisceralis was found as muscle with highest fiber length and coccygeus was found as muscle with highest PCSA. Also, aging was found as an important factor, which leads higher collagen accumulation (Alperin et al., 2016).

Muscle tissue in different life stages

Age is one of the important parameters of the muscle function. Different life stages change the contractile parts as well as non-contractile parts in the skeletal muscle. Aging is the most popular issue to explore the changings in the muscle tissue. Therefore the researches on sarcopenia are becoming important.

Effect of aging

Decreased muscle fiber lengths, which are attributed to decrease in number of sarcomere in series, have been observed in aged people. Decreased fiber length indicates decreased shortening velocity since aging causes fiber type changes. With aging type 1 fibers are preserved while Type 2 fibers are decreased. Additionally, non-contractile structures increase their connective tissue quantity. These changes lead higher passive longitudinal stiffness. This stiffness cannot be attributed only to connective tissue layer alterations, but also extracellular matrix changings. Obvious muscle mass loss is seen which accompanied by decrease of satellite cells associated with type 2 fibers. Right after, fat infiltration and accumulation is observed. Force times velocity reduces approximately 2.9% per year after 65 years of age. Sarcopenia affects muscles of both upper and lower extremities as well as spinal group (Miljkovic et al., 2015; Frontera, 2017).

Parameters of the architecture are also altering. Fiber length, PCSA and pennation angle are decreased in older population. Fiber length decrease is an indicator of serial sarcomere loss. Also decrease of anatomical cross sectional area reduces the force generation ability of the muscle (Kuyumcu et al., 2016; Frontera 2017; Ozcakar et al., 2018; Porcari et al., 2018).

Effect of childhood

Limited data is present in the literature about muscle architecture of the children. Stephensen et al. showed 15.83° pennation angle in lateral gastrocnemius in thirty-eight boys aged 9.86 ± 1.30 years (Stephensen et al., 2014). Moreau et al, found the pennation angles for rectus femoris as 12.32° ± 3.45° and 13.57° ± 3.08° for vastus lateralis in typically developing children aged 11.3 ± 3.0 years (Morse et al., 2005). O'Brien at al evaluated the muscle-tendon unit architecture in boys (8.9 ± 0.7 years) and girls (9.4 ± 0.8 years) and compared with adults. They assessed vastus medialis, vastus lateralis, vastus intermedius and rectus femoris muscles. Fascicle lengths were found different between children and adults, pennation angles were relatively similar. However, proximal, distal and central parts of the muscles show differences on fascicle length and pennation angles (O'Brien et al., 2010). Morse et al. found similar results with O'Brien. They compared the architectural features of lateral gastrocnemius muscle between early pubescent boys (10.9 ± 0.3 years) and adult men (25.3 ± 4.4 years). No difference was found in pennation angle and in the ratio of Lf/Lm between groups in resting. However pennation angle were found 21% smaller during contraction. They also found that specific force was higher in boys. Although some architectural parameters were similar, force production was found different. On the other hand Kannas et al. showed differences on pennation angles between boys (11.2 ± 0.26 years) and men (22.3 ± 2.01 years). Children displayed lower pennation angle of 4–6° on average (Kannas et al., 2010). It was suggested that pennation angle increases linearly during growth.

Architectural adaptation of the muscle to pathological conditions

Denervation

Recently, botulinum toxin is used in upper motor neuron lesions and lead transient denervation in studies. It leads strength loss and connective tissue alterations similar to peripheral nerve lesions. Few studies investigated the effect of denervation on skeletal muscle. Kawano et al. found decrement in pennation angles in spastic gastrocnemius after botulinum toxin treatment (Kawano et al., 2018). Tok et al. found similar results in gastrocnemius muscles of the patients with stroke. After injection, pennation angles were found lower and fascicle lengths were found higher (Tok et al., 2011). Chemical toxin induced denervation model seems to affect the muscle architecture.

Spasticity

Although spasticity is accepted as an overuse pattern, architectural and structural adaptation showed several features of disuse model. Literature and clinical approaches mainly focused on central nervous system. However recent studies have shown skeletal muscle adaptation to the spasticity (Lieber, 2002a,b,c). Thus, re-education of the spastic muscle, instead of inhibiting, became important. Older treatment methods were based on the inhibiting the spastic muscle to augment the function of the antagonists (Nair and Marsden, 2014). Due to current knowledge, we can say that preserving and improving the mechanical and architectural properties of spastic muscle are crucial as well as cortical re-education.

Many studies showed increased stiffness values in spastic muscle (Lieber, 2002a,b,c; Lieber and Friden, 2002). Increased extracellular matrix and collagen accumulation change the viscoelastic properties due to altered drive from cortex (Friden and Lieber, 2003). These changings decrease the elasticity. Even if cortical reorganization improves, force-generating capacity reduces (Lieber et al., 2004).

There are inconsistent values for fascicle length of spastic muscles in literature. Kawano et al, evaluated architectural features of gastrocnemius muscle in children with cerebral palsy (CP) and compared with healthy peers. They found higher pennation angles and shorter fascicle lengths in spastic gastrocnemius. But they did not measure the fiber lengths (Kawano et al., 2018). Kruse et al. found shorter fiber lengths in gastrocnemius in children with CP in comparison with typically developing children. They also found higher pennation angle values in CP group although muscle thicknesses were similar. In conclusion, they proposed that pennation angle increment was expected due to the similar muscle thickness (Kruse et al., 2018). These varied results may be seen due to heterogeneity of the spasticity levels. Kesikburun et al, found similar fascicle length and pennation angle values in gastrocnemius muscles of stroke patients. Muscle thicknesses were same as previous study (Kesikburun et al., 2015). On the other hand Yang et al. demonstrated higher pennation angle and lower fascicle length as compared to unaffected limb (Yang et al., 2014).

In addition the fiber length and pennation angle adaptation to the spasticity, adaptation of sarcomere is the most impressive issue. Lieber and Fridén, investigated elongated sarcomeres in spastic flexor carpi ulnaris (FCU) muscle in children with upper motor neuron disorders. FCU muscles with severe spasticity had sarcomere length of $3.48 \pm 0.44\ \mu m$. Besides, sarcomere length increased with passive wrist extension (Lieber, 2002a,b,c; Lieber and Friden, 2002). Based on this data, stretching of spastic muscle may worsen the contractile unit which leads further dysfunction. It seems necessary to keep muscle in mid-range to preserve sarcomere length.

Immobilization

Many studies have investigated the effect of immobilization on muscle size and strength. However limited numbers of studies have analyzed muscle architecture after immobilization. Immobilization after injury caused decrease in fascicle length and pennation angle of lateral gastrocnemius muscle in the study of Narici et al. (Narici et al., 2016). Also, Bleakney et al. found decrease in pennation angle and fiber length of vastus lateralis in the subjects who had femur and tibia fracture after immobilization period (Bleakney and Maffulli, 2002). De Boer et al. investigated the effect of 5 weeks horizontal bed rest on medial gastrocnemius, vastus lateralis, tibialis anterior and biceps brachii muscles in healthy men. Fiber length and pennation angle were found decreased in gastrocnemius and vastus lateralis whereas unchanged in tibialis anterior and biceps brachii muscles (de Boer et al., 2008). We conclude that unloading responses may differ between antigravity and non-antigravity muscles. Muscles with different assignments respond different to the unloading.

Using of a plaster cast is another method to create an immobilization model. Narici showed fascicle length and pennation angle decrement in vastus lateralis muscle just after 8 days (Narici et al., 2016). These findings suggest that loss of serial sarcomere occurs very early during immobilization. These early alterations should be remembered when considering rehabilitation approaches after immobilization and planning long-duration orthotic devices.

Muscle architecture based planning in rehabilitation approaches

Stretching

In review article of Freitas et al. suggested that stretching programs less than 8 weeks did not alter the muscle properties. However, several studies showed that short term stretching programs induced elongation in the fiber length while reducing the pennation angle (Freitas et al., 2018). Abellaneda found increment in fiber length and decrement in pennation angle in medial gastrocnemius muscle during passive stretching. When ankle joint moved from 10° plantarflexion to 30° dorsiflexion, alterations in fiber features were changed linearly. During stretching 71.8% of elongation was occurred in contractile part whereas 28.2% in tendinous part (Abellaneda et al., 2009). It should be kept in mind that short term stretching mainly alters sarcomere structure. Instant increase in fiber length is seen as a result of sarcomere elongation. Therefore early stretching programs after muscle strain should be reviewed.

Peixinho et al. applied stretching training to the lateral gastrocnemius muscle of rats 3 times per week for 8 weeks. Muscles were stretched 60 seconds for 10 times. After 12 sessions of stretching program, pennation angle was found reduced; fiber length and sarcomere length were found increased. These changes were seen only in contractile part of the muscle but not muscle-tendon unit (Peixinho et al., 2014).

Several studies revealed that stretching led serial sarcomere adding, in other words ‘sarcomerogenesis’. It is important to get muscle back to the optimal operating range especially in the presence of elongated sarcomere.

However most of the studies were performed in lab with animals. De Jaeger applied intermittent stretching on rabbit plantarflexor muscles passively and statically 3 times a week for 4 weeks with using a cyclic-stretching device. One session consisted of 25 stretching cycles. Stretched soleus showed increase in serial sarcomere numbers but not medial gastrocnemius and plantaris muscles. Higher slow-twitch fiber ratio was indicated to refer to explain this adaptation (De Jaeger et al., 2015). It seems that the muscles with higher Type 1 fiber content are more convenient for stretching for sarcomerogenesis.

Exact duration to achieve sarcomerogenesis is not clear. But it's certain that the process is time dependent adaptation. Peviani et al. compared 10 days and 15 days passive stretching (10 sets, 10 minutes, 1 minute duration, 30 seconds rest) in soleus muscle of rats. They observed sarcomeorgenesis after 15 days of stretching (Peviani et al., 2018).

Passive stretching increases the fiber length. We assume that this increment also induce increment in excursion. Literature in animal studies almost agrees that with passive stretching, sarcomere number can be increased. However its validity, duration and method are not clear for human. Possibility of these adaptations should be considered in all static stretching approaches as well as orthosis planning for contractures.

Although many studies have been performed on stretching, the architectural features including pennation angle and muscle fiber arrangement has not been taken into consideration sufficiently. For example can effects of static stretching be same in muscles with higher and lower pennation angles? We can ask same question for the muscles with longitudinal fiber arrangement and pennate muscles. Pennate muscles respond to stretching as decreasing their pennation angle and increasing the fiber lengths. What about the longitudinal oriented muscles? Do biceps brachii and pronator teres adapt to the stretching in same way? Based on these questions stretching regimes should be planned according to their fiber arrangement and/or pennation angle values. Because stretching of biceps brachii may deteriorate the sarcomere lengths. These points deserve well-designed researches.

Strengthening

The primary adaptation to the strengthening is increase in PCSA of the whole muscle and of the individual muscle fibers due to increase in myofibril size and number. Pennation angle increase is another consequence of concentric strength training. PCSA increase with pennation angle, thus less force from each fiber is transmitted to the tendon due to their increasingly oblique angle of pull. For this reason strength training is important on tendinopathy. Any increase in pennation angle would be expected to increase force (Folland and Williams, 2007). Also, the increment in pennation angle reflected the increase in parallel sarcomeres (Blazevich et al., 2006).

Coratella et al. showed fiber length increment of vastus lateralis muscle in both sex after 8 weeks eccentric training. However pennation angle increase was found only in women (Coratella et al., 2018). Similarly Guex et al. found fiber length increase after 3 weeks eccentric training in both short and long muscle length of hamstring muscle but pennation angle did not change (Guex et al., 2016). To increase the fiber length and excursion of a muscle with higher PCSA and lower fiber length, eccentric training should be implanted in addition to the stretching.

On the other hand concentric training leads increment in pennation angle and PCSA, and decrement in fascicle length. Kim et al. found increase in pennation angle and decrease in fascicle length of supraspinatus muscle after 8 weeks concentric training (Kim et al., 2015). Franchi et al. compared the architectural response to eccentric and concentric resistance training. They found similar in muscle volume. However increases in fiber lengths were found higher in eccentric group. Pennation angles were higher in resistance training group (Franchi et al., 2014). For transforming a muscle for higher excursion or higher PCSA, choosing the strengthening method is crucial.

Neuromuscular electrical stimulation

Neuromuscular electrical stimulation (NMES) is a well-known re-education method. Muscle tissue alterations after NMES have been investigated in many studies. However its effect on muscle architecture has not been analyzed in detail. Variation of stimulation parameters and muscle fiber types may be the important obstacles behind this. Notwithstanding few researches give insight into the effect of NMES on muscle architecture. Karabay et al. investigated the effect of NMES on tibialis anterior muscle architecture in children with CP. NMES was applied to the muscle 30 minutes, 5 days per week for 4 weeks. Twenty-five hertz frequency and 250 μm duration were chosen. Only PCSA was higher after NMES. Other parameters including pennation angle and fascicle length did not change (Karabay et al., 2015). This result may not be surprising due to the stimulation parameters. Because tibialis anterior is known as a fast contracting muscle, and the chosen frequency fits for a slow contracting muscle. Choosing proper parameter for NMES may alter the results.

Gondin et al. used direct femoral nerve stimulation to stimulate quadriceps femoris for 8 weeks. They found increment in vastus lateralis pennation angle. They also found anatomical cross sectional area increase in vastus lateralis, vastus intemedius and vastus medialis. Although the stimulation parameter was same different responses were acquired (Gondin et al., 2005). Probably muscles' different architecture and fiber type cause different reactions. But it is almost impossible to determine the correct parameters for each muscle.

Tendon transfers

Tendon transfer is an impressive procedure of the muscle adaptation as well as cortical reorganization. Previous reports suggested fiber length and PCSA based transfer planning by Lieber and Fridén. Lieber and Fridén have offered to choose the donor muscle which approximate to the paralytic muscle according to the scatter graph of the muscles based on fiber length and PCSA (Lieber and Friden, 2000; Lieber, 2002a,b,c; Lieber and Ward, 2011). However functional results and changes in muscle architecture parameters after offered view have not been investigated adequately.

Muscle geometry changes are determined in a few studies. Huijing and Maas evaluated the PCSA and sarcomere number adaptations after flexor carpi ulnaris (FCU) to the extensor carpi radialis brevis (ECRB) and longus (ECRL) in rats. FCU had 19% smaller PCSA and 25% less sarcomere number after 5 weeks of the surgery. These results were explained with stretching of the FCU tendon due to transfer (Huijing and Maas, 2016). We think 5 weeks may not be sufficient duration to obtain adaptive changes or tendon tension might be excessive. Takahashi et al. transferred extensor digitorum muscle of rabbit with a sarcomere length of 3.7 μm. They observed a rapid increase in serial sarcomere number 1 week after surgery. Until 8 weeks, this increased sarcomere number decreased while the sarcomere length remained constant. At 8th week same sarcomere numbers were seen as control group. Also tendon length was found increased. Sarcomere length rapidly decreased from 3.28 ± 0.09 μm 1 day after surgery to 2.56 ± 0.04 μm 1 week after surgery and to 2.2 μm 8 weeks after surgery, approximately (Takahashi et al., 2010). Even transfer of highly stretched muscle can show adaptation in a short time. However this adaptation may not provide enough function. In another study of Takahashi et al, extensor digitorum muscle of second toe of rabbit was stretched up to 3.7 μm and transferred for the ankle extensor retinaculum. At the end of 4th week, sarcomere numbers were found increased while muscle excursion was decreased (Takahashi et al., 2012). Although a great muscular adaptation was seen in a short period of time, this adaptation did not reflect on function. To reach functional results after tendon transfer may require longer durations than expected.

Mostly, therapists meet patients after surgery and rehabilitation period is usually began with end of the immobilization. As literature mentioned, many alterations in transferred muscle including sarcomere adaptations and extracellular matrix proliferation occur (Friden and Lieber, 2002). Soon after the cast is removed, it is difficult to activate the muscle. Literature lacks the research which investigates the factors related achieving functional results. Cortical plasticity ability, planning the transfer based on scatter graphs, applied tension during surgery, optimal immobilization duration, and severity of lesion may all affect functional recovery. As muscle architecture adaptations are described in this chapter, I would like to introduce an architecture-based rehabilitation approach.

Actually, there is a need for preparing the patient to surgery. Thus, selected muscle for transfer can be transformed before the surgery. We know that concentric strengthening and NMES increase the PCSA. Locations of paralytic and donor muscles based on scatter graph will guide us to determine loading method. If a muscle is going to be transferred to replace a muscle with higher PCSA, it should be getting strengthened with concentric loading and NMES. On the other hand if we need excursion (if paralytic muscle has high PCSA according to the scatter graph), we should stretch the muscle over 8 weeks in addition to eccentric training to extent the fiber lengths. This planning should also continue after surgery and immobilization period. During the process, other well-known approaches for edema management, cortical reorganization, orthosis and functional activities should also be maintained.

Conclusion

There is a strong necessity for developing 'muscle architecture based rehabilitation' approaches. With using widespread imaging methods including B Mode ultrasound and magnetic resonance imaging techniques, researches which are focusing on stretching, tendon transfer rehabilitation should be designed.

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Chapter 9

Architecture of tendon and ligament and their adaptation to pathological conditions

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Introduction

Tendons and ligaments are bands of aligned, collagenous connective tissue that transmit loads within the musculoskeletal system. They are flexible structures and extraordinarily strong in resisting the tensile loads. Tendons are defined as the connective tissue that connects muscle to bone. The Anglo-Saxon word for tendon is "sinew" which means "strong" or "tough". Ligaments are defined as the connective tissue that connects bone to bone. Tendons and ligaments play a significant role in providing the joint function and overall musculoskeletal biomechanics. Illustrated tendon and ligament for knee joint were shown in Fig. 9.1. Normal joint function is contingent upon normal tendon and ligament function (Winkelstein, 2013; Martin et al., 2015).

This chapter discusses the architecture of tendon and ligament under the basic science principles and reviews the normal and pathological biomechanical properties and behaviors following an injury or pathology of tendon and ligament, separately. Tissue healing and factors that affect the biomechanical function of tendon and ligament were included. The architecture of tendon and ligaments may be defined with the basic science including the following subtitles: composition and structure, function, biochemical constituents, vascular and neural supply, and biomechanical properties. Knowing the architectural feature is utmost important for understanding loading, injury and healing characteristics, and responses to the different situations and pathologies (Weintraub, 2003; Nordin and Frankel, 2012).

Architecture of tendons

Structure

Tendons are tough cords composed of closely packed white fibers of connective tissue. They serve to attach muscles to internal structures such as bones or other muscles. Sometimes when the muscle involved, the tendon is not a cord but a thin sheet known as an aponeurosis (2001). Most skeletal muscles are attached to bone or cartilage by a tendon, aponeurosis, or by direct attachment. Tendon and cartilage cells originate from common mesodermal compartments (Tozer and Duprez, 2005). Trunk tendons have been shown to develop differently from limb tendons that they originate from the dorsal region of sclerotome adjacent to the dermomyotome from which the myogenic cells that form muscles. From embryologic origins to tissue, the cells of both tendon and ligament condense and differentiate into fibroblasts. The fibroblasts align in rows and begin fibrinogenesis. Elastic fibrinogenesis involves the development of fibrillin microfibrils. Tendon and ligament growth includes increases in collagen fibril diameter and tissue length up to adulthood (Winkelstein, 2013).

Structurally, the tendon is composed of tenoblasts and tenocytes lying within a network of extracellular matrix (ECM). Tenoblasts and tenocytes account for 90–95% of the cellular elements of tendons. The remaining 5–10% of the cellular elements consists of chondrocytes at the bone attachment and insertion sites, synovial cells of the tendon sheath, and vascular cells, including capillary endothelial cells and smooth muscle cells of arterioles (Sharma and Maffulli, 2006).

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Tendons have a hierarchical structure. The largest structure is the tendon itself. The tendon then is split into smaller entities called fascicles. The fascicle contains the basic fibril and the fibroblasts. Fibrils split subfibrils, myofibrils, and collagen molecules (Fig. 9.2). This type of hierarchical structure aligns fiber bundles with the long axis of the tendon and affords the tendon's tensile strength. This structure appears as a "crimp pattern". The crimp is the waviness of the fibril when longitudinal sections of the tendon are viewed in a polarized microscope. This contributes significantly to the nonlinear stress−strain relationship (Whittaker and Canham, 1991; Wang, 2006; Liu et al., 2008).

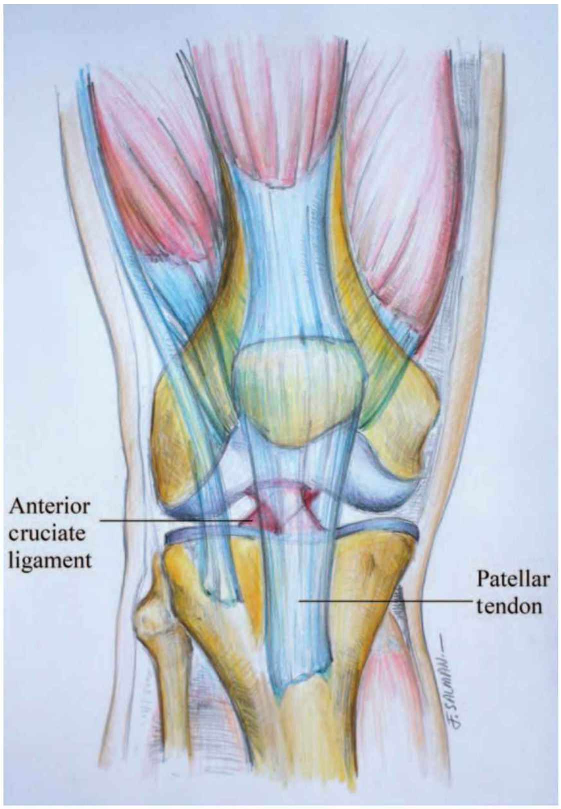

FIGURE 9.1 Patellar tendon and anterior cruciate ligament illustrations. *Illustrated by F. Salman, PhD.*

A tendon is usually round, oval, or elongates in cross-section and consists of fascicles of collagen fibers, which are embedded in a ground substance and generally run parallel to the long axis of the tendon. Connective tissue is associated with a tendon in the form of a sheath on its surface, called epitenon. The epitenon contains vascular, lymphatic, and nerve supply (Fig. 9.2). This areolar tissue is continuous with the endotenon, a loose connective tissue that permeates the substance of the tendon, separating the fascicles and providing a route for vessels and nerves. The epitenon, on the surface of the tendon, is continuous not only with the endotenon but also with loose areolar tissue, the paratenon. This loose arrangement consists of type-I and type-III collagen fibers, some elastic fibers, and an inner lining of synovial cells. It allows minimal resistance to movement of the tendon through tissues. Synovial tendon sheaths are found in the places where the mechanical stress is increased and when lubrication is needed. The inner synovial sheet functions as a membrane for synovial fluid production. The fibrous sheath condensates as a pulley and it functions as a fulcrum for tendon function (Sharma and Maffulli, 2005).

Tendons connect bone and muscles at their ends. The tendon−bone junction is called the enthesis. There are two types of enthesis: the fibrous enthesis, and the fibrocartilaginous enthesis. At the fibrous enthesis, the tendon attaches to the periosteum during childhood or to the bone itself during adulthood. The fibrocartilaginous enthesis includes a transitional zone of hyaline fibrocartilage. It distributes mechanical loads (Benjamin et al., 2002). The enthesis can bear tensile, compressive and shear forces, and it is estimated that the tensile forces at this site may be four times that of the tendon mid-substance. These forces may lead to histopathological

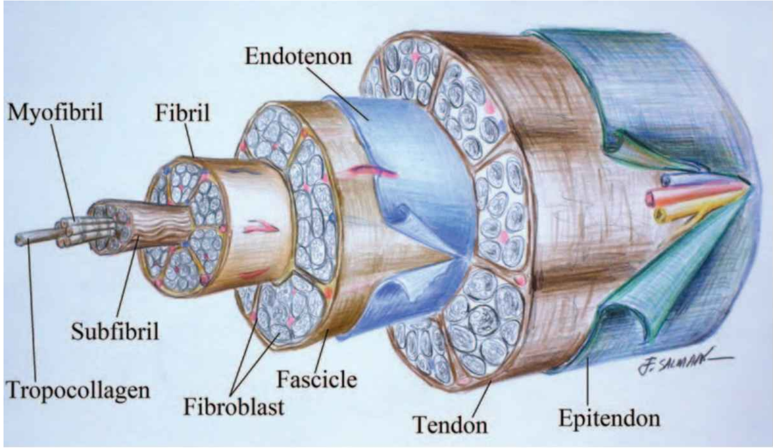

FIGURE 9.2 Schematic illustration of the hierarchical structure of tendon. *Illustrated by F. Salman.*

changes of fibrocartilage at the tendon–bone junction (Benjamin et al., 2002; McGonagle et al., 2003; Thomopoulos et al., 2006). The myotendinous junction transfers muscular forces to the tendon and enhances muscle growth. At this junction, the tendon's collagen fibrils are inserted into deep recesses formed by myofibroblasts, which allow tensile forces generated by contractile proteins (actin and myosin) of muscle fibers. This structure also reduces tension on tendons during muscle contraction. However, the myotendinous junction is also the weakest point of the muscle-tendon unit (Trotter, 2002; Sharma and Maffulli, 2005; Wang, 2006).

Composition and biochemical constituents

Tendons have relatively few cells, called tenocytes, and an abundant ECM. The primary role of the tenocytes is to control tendon metabolism (production and degradation of the ECM) and to respond to the mechanical stimuli applied to the tendon, particularly tensile loads (Nordin and Frankel, 2012). The cellular material occupies approximately 20% of the total tissue volume, while the ECM accounts for the remaining 80%. Approximately 55–70% of the matrix consists of water, and a substantial part of this is associated with the proteoglycans in the ECM. The remaining percentage are solids composed mainly of collagen (60–85%), an inorganic substance such as proteoglycan (<0.2%), a small amount of elastin (2%), and other proteins (4.5%) (Sharma and Maffulli, 2006; Nordin and Frankel, 2012).

Tendons are rich in collagens. Type I collagen accounts for about 60% of the dry mass of the tendon and about 95% of the total collagen (Sharma and Maffulli, 2006). The main function of Type I collagen is to sustain large tensile loads while allowing for some level of compliance or mechanical deformation (Benjamin et al., 2008). The remaining 5% consists of types III and V collagens. In normal tendons, type III collagen is mainly located in the endotenon and epitenon. Type III collagen forms smaller, less organized fibrils. Type V collagen is intercalated into the core of type I collagen fibrils and regulate fibril growth (Gomes, 2015). Other collagens, including types II, VI, IX, X, and XI, are present in trace quantities in tendons. These collagens are mainly found at the bone insertion site of fibrocartilage, where they strengthen the connection by reducing stress concentration at the hard tissue interface (Benjamin et al., 2002; Wang, 2006).

The basic structural unit of collagen is tropocollagen. It is a long, thin protein produced inside a cell and secreted into ECM as procollagen. Collagens in the matrix are cross-linked. The cross-linking increases Young's modulus of the tendon and plays an essential role in creating an interconnected fibrillar material of tunable toughness and strength (Depalle et al., 2015).

Besides collagens, tendons also contain proteoglycans in small quantities. The proteoglycan content varies at the site of the tendon and depends on the mechanical loading conditions of the tendon (Wang, 2006; Nordin and Frankel, 2012). The strongly hydrophilic nature of proteoglycans participates in tendon repair and regeneration (Sharma and Maffulli, 2006). There are two main proteoglycans, aggrecan, and decorin. Aggrecan holds water within the fibrocartilage and resists compression. Decorin, a small leucine-rich proteoglycan, is located on the surface of the middle portions of collagen fibrils and is thought to facilitate fibrillar slippage during mechanical deformation. These include tenascin-C and fibronectin. Tenascin-C contributes to the mechanical stability of the ECM through its interaction with collagen fibrils. Tenascin-C may play a role in collagen fiber alignment and orientation in tendinopathy. Fibronectin is located on the surface of collagens, and its synthesis increases to facilitate wound healing (Elefteriou et al., 2001; Roughley, 2006; Wang et al., 2012).

Additionally, tendons contain elastin, which composes about 2% of the dry weight of the tendon. It has been shown that elastic fibers present a close connection with the tenocytes (Pang et al., 2017). Elastin localizes to the interfascicular matrix of energy storing tendons and it may be more disorganized with aging (Godinho et al., 2017). The elastic fibers, which comprise elastin and microfibrillar proteins, may contribute to the recovery of the crimp configuration of the collagen fibers after stretching. Although endothelial cells, synovial cells, and chondrocytes are present in tendons, fibroblasts (tenoblasts and tenocytes) are the dominant cell type. Tendon fibroblasts align in rows between collagen fiber bundles. Fibroblasts are responsible for synthesizing ECM proteins (e.g., collagens, fibronectin, and proteoglycans), producing an organized collagen matrix, and remodeling it during tendon healing (Wang, 2006; Chapman et al., 2016).

Function

Tendon and ligament compliance allows elastic energy to be stored and returned to offset energy fluctuations of the body's center of mass during locomotion, conserving muscle work and reducing the metabolic energy cost of locomotor movement (Fratzl, 2008). The purpose of the tendon in attaching muscle to bone is to enable the power of the muscle to transfer over a distance (2001). During various phases of movements, the tendons are exposed to longitudinal, transversal and rotational forces, direct contusions and pressures. The three-dimensional internal structure of the fibers forms a buffer against forces of various directions, thus preventing damage (Kannus, 2000).

Tendon architecture greatly affects the storage and recovery of elastic strain energy (Biewener, 2016).

Tendon compliance may also reduce the cost of muscle contraction, by reducing a muscle's contractile velocity and length change for a given movement, as well as increasing the power output of muscle-tendon units. This power enhancement requires a temporal decoupling of muscle work to stretch the tendon from the subsequent more rapid release of elastic strain energy from the tendon. However, Holt et al. proposed that the energetic benefits of tendons were derived primarily from their effect on muscle and limb architecture rather than their ability to reduce the cyclic work of muscle (Holt et al., 2014). In addition, because tendon compliance impedes position control, the thickness of many tendons suggests that having sufficient stiffness, rather than strength, is a key structural requirement (Martin et al., 2015). Because of their high tensile strength and stiffness, tendons transmit muscle forces over long lengths with minimal "in-series stretch". Nevertheless, tendon compliance is important for storing and releasing elastic energy to reduce locomotor costs, as well as for allowing muscles to contract economically at lower velocities and strains, and for minimizing the risk of damage to musculoskeletal structures. Given that the maximum tensile stress produced by skeletal muscles is ~200–400 kPa, a tendon on the order of the only ~1/1000th the physiological cross-sectional area of a muscle can, therefore, safely transmit the muscle's force without failing (Martin et al., 2015; Biewener, 2016). By transmitting tensile stresses, as flexible structures tendons and ligaments also easily bend and change shape to accommodate changes in joint position and skeletal orientation. All collagen I-based tissues exhibit non-linear elastic properties, reflected by their "J"-shaped stress–strain curves. This means that tendons and ligaments exhibit greater compliance at low stresses than at intermediate to higher stresses, enhancing their energy absorption capacity at low-stress levels. This is clearly important given that these structures must function over a large number of loading cycles during an individual's lifetime (Fratzl, 2008). The tendons themselves also contribute to holding each other in a position such as the tendons at the dorsum of hand and foot. A collection of tendons as a concept of a 'supertendon' forms a tendon network and functions in the character of the associated muscle. Moreover, tendons are related to the structures such as joint capsules, tendon sheaths, pulleys, retinacula, fat pads, bursae and fascia as a concept of an 'exoskeleton' (Benjamin et al., 2008).

Biomechanics and mechanical properties

Tendons transmit force generated by muscle to bone and act as a buffer by absorbing external forces to limit muscle damage. Tendons exhibit high mechanical strength, good flexibility, and an optimal level of elasticity to perform their unique role. Tendons are viscoelastic tissues, which display stress relaxation and creep. The viscoelastic characteristics contribute to the unique mechanical behavior (Sharma and Maffulli, 2006).

A load–elongation curve or typical tendon stress–strain curve offers information regarding the tensile capacity of a tendon–ligament structure after loading a tendon or a ligament to failure. In a load–elongation curve, the stiffness of the structure (N/nm) is the slope of the curve between two limits of elongation (Mow and Huiskes, 2005). It represents how much load and or elongation the structure can sustain before it fails. The ultimate load (N) is the highest load placed on the structure before failure. The ultimate elongation (mm) is the maximum elongation of the complex at failure. Finally, the energy absorbed at failure (N/mm) is the area under the entire curve, which represents the maximum energy stored by the complex (Nordin and Frankel, 2012) (Fig. 9.3).

In a stress–strain diagram, the elongation is often expressed as strain (ε), which is the deformation of the tissue calculated as a percentage of the original length of the specimen. The force per unit of area (in this case, the total tensile load per unit by the cross-sectional area of the tendon or ligament under analysis) is expressed as the stress (σ). From stress–strain curves, a modulus (N/mm^2 or MPa) is obtained from the linear slope of the stress–strain curve between two limits of strain (deformation) where the tensile strength (N/mm2) is the maximum stress achieved, the ultimate strain (in percentage) is the strain at failure, and the strain energy density (MPa) is the area under the stress–strain curve (Fratzl, 2008; Nordin and Frankel, 2012).

Typical tendon stress–strain curve has an initial toe region, where the tendon is strained up to 2%. This toe region represents the stretching-out of the "crimp-pattern" of a tendon. Beyond this point, the linear region of the stress–strain curve, where the tendon is stretched less than 4%, starts. In this region, collagen fibers lose their crimp pattern. The slope of this linear region is referred to as Young's moduli of the tendon. If the strain remains below 4%, the tendon behaves in an elastic fashion and returns to its original length when unloaded. However, if the tendon is stretched over 4%, microscopic tearing of tendon fibers occurs. Beyond 8–10% strain, macroscopic failure occurs. And further stretch causes tendon rupture (Fig. 9.4) (Xu and Murrell, 2008).

Like other soft tissues including ligaments and skin, tendons are viscoelastic and sensitive to different strain rates. The viscoelastic behavior of the tendon likely results from collagen, water, and interactions between collagenous proteins and non-collagenous proteins. The viscoelasticity of a material is defined by stress-relaxation, creep, and hysteresis. Because of their viscoelasticity,

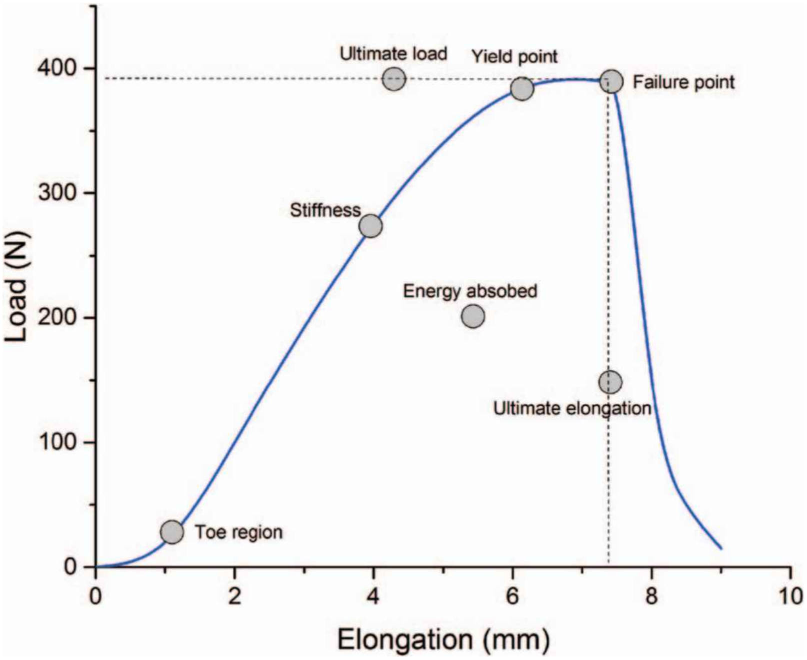

FIGURE 9.3 Load–elongation curve of a tendon–ligament structure.

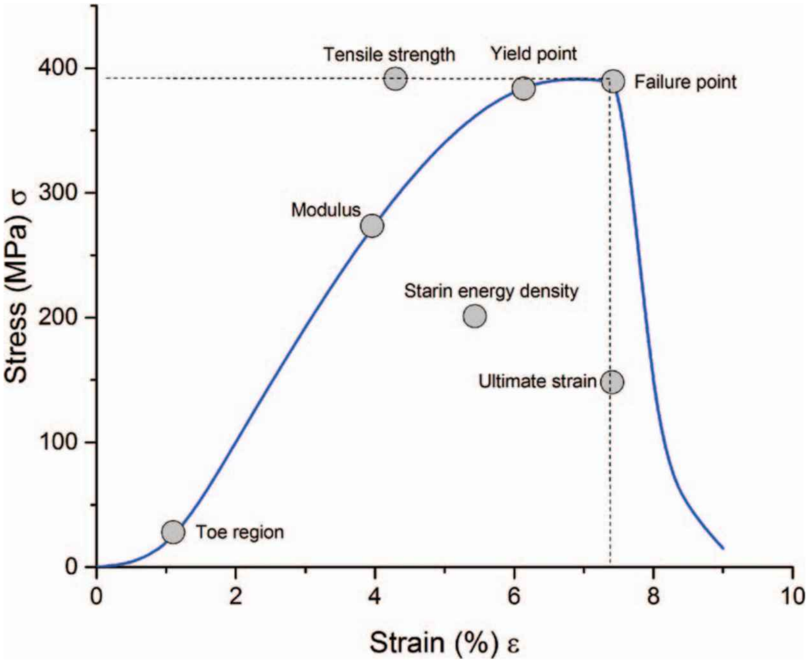

FIGURE 9.4 Stress–strain curve of a tendon–ligament structure.

tendons are more deformable at low strain rates. Therefore, the tendons absorb more energy but are less effective in transferring loads. At high strain rates, tendons become less deformable with a high degree of stiffness and are more effective in moving large loads (Józsa and Kannus, 1997).

Two standard experimental tests are used to illustrate the viscoelastic, time-dependent, nonlinear behavior of ligaments and tendons. These are the stress-relaxation and the creep-deformation tests. In a stress-relaxation test (load-relaxation test), the specimen is stretched (deformed) to a constant length, so the strain is kept constant over an extended period allowing the stress to vary with time. When the length is held constant, the stress decreases rapidly at first and then more slowly. When the stress-relaxation test is repeated cyclically, the decrease in stress gradually becomes less pronounced. A creep-deformation test, on the other hand, involves subjecting the specimen to a constant load (the stress is kept constant over an extended period) while the length (deformation) gradually increases with time. The strain increases relatively quickly at first and then more and more slowly. When this test is performed cyclically, the increase in strain gradually becomes less pronounced. The clinical application of a constant low load to the soft tissues over a prolonged period, which takes advantage of the creep response, is a useful treatment for several types of deformities (Nordin and Frankel, 2012) (Figs. 9.5 and 9.6).

Vascular supply

Tendons receive their vascularization from three main sources: the intrinsic systems at the myotendinous junction and osteotendinous junctions, and from the extrinsic system via the paratenon or the synovial sheath. Small arterioles enter the tendon from adjacent muscle and run longitudinally in the interfascicular areolar tissue, accompanied by veins and Iymph vessels. These longitudinally situated vessels anastomose freely with small vessels from adjacent para-tendon tissue or synovial sheaths by

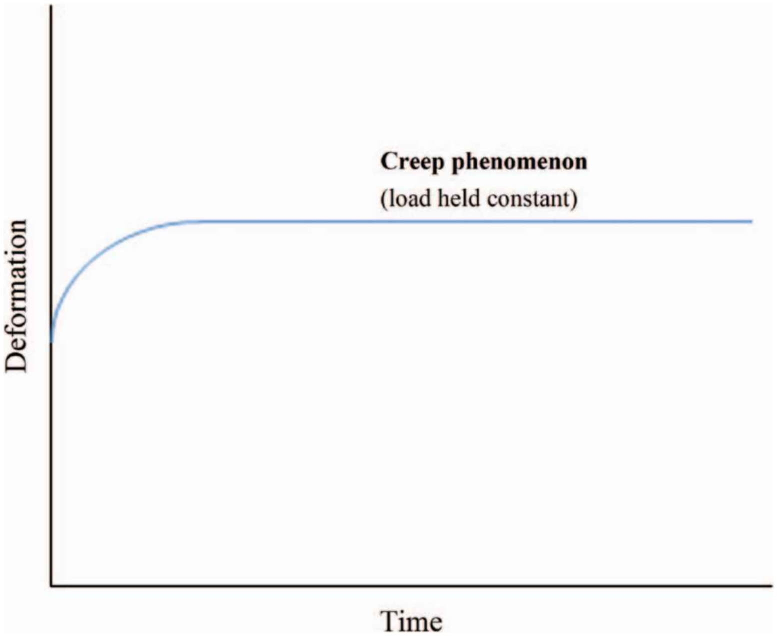

FIGURE 9.5 Load relaxation graph.

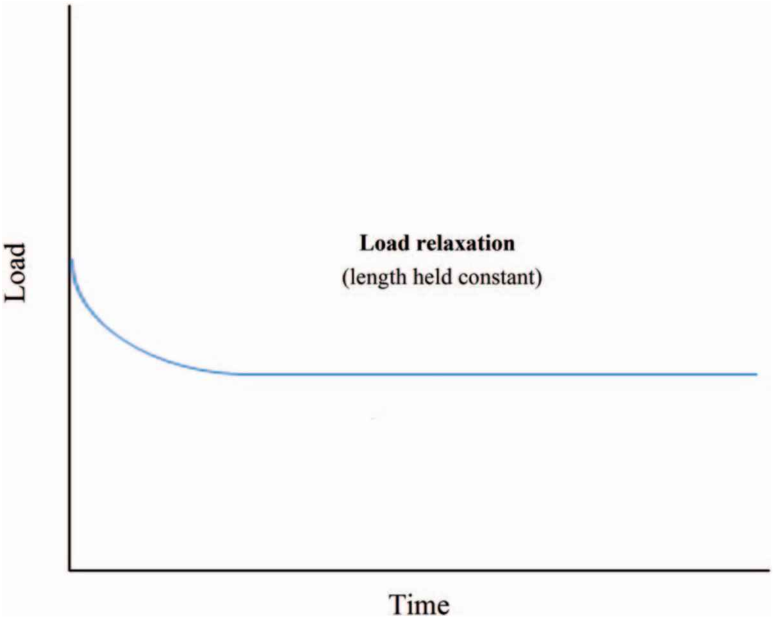

FIGURE 9.6 The creep response.

means of the mesotendon. The ratio of vascular supply from the intrinsic to extrinsic systems varies from tendon to tendon. Tendon vascularity is compromised at junctional zones and sites of torsion, friction or compression. In general, tendon blood flow declines with increasing age and mechanical loading, and peak exercise (Sharma and Maffulli, 2005; Sharma and Maffulli, 2006).

The vascular supplies of tendons in regions where they wrap around bony pulleys are diminished. As certain tendons (e.g. fibularis longus and flexor hallucis longus) can press against the bone at more than one location between the myotendinous junction and the enthesis, it follows that they can have a corresponding number of poorly vascularized regions. Such areas of diminished or absent blood supply are of particular clinical significance because they are commonly the sites of tendon degeneration and/or rupture (Benjamin et al., 2008).

Neural structures

Tendon innervations originate from cutaneous, muscular, and peritendinous nerve trunks (Sharma and Maffulli, 2005). The nerve supply of tendons appears to be almost entirely afferent, and specialized afferent receptors, neurotendinous endings, exist in tendons, especially near the muscle–tendon junction. Innervation of intact healthy tendons is localized in the surrounding structures, i.e paratenon, endotenon, and epitenon, whereas the tendon proper is practically devoid of neuronal supply (Ackermann et al., 2016). Nerve fibers form rich plexuses in the paratenon, and branches penetrate the epitenon. Most nerve fibers do not actually enter the main body of the tendon but terminate as nerve endings on its surface. Nerve endings of myelinated fibers function as specialized mechanoreceptors to detect changes in pressure or tension. The Golgi tendon organs are most numerous at the insertion of tendons into the muscle. Unmyelinated nerve endings act as nociceptors, and sense and transmit pain. Both sympathetic and parasympathetic fibers are present in the tendon (Sharma and Maffulli, 2005).

In response to injury, the expression of neuropeptides is significantly altered in a temporally orchestrated manner, suggesting a well-synchronized mechanism in nociception and tissue repair. Tendon innervation after injury and during repair is found as extensive nerve ingrowth into the tendon proper, followed by a time-dependent emergence of different neuronal mediators, which amplify and fine-tune inflammatory and metabolic pathways in tendon regeneration. After healing nerve fibers retract to the tendon envelope. In tendinopathy innervation has been identified to consist of excessive and protracted nerve ingrowth in the tendon proper, suggesting pro-inflammatory, nociceptive and hypertrophic (degenerative) tissue responses. In metabolic disorders such as diabetes-impaired tendon healing has been established to be related to dysregulation of neuronal growth factors (Ackermann et al., 2001).

Summary of tendon architecture

Tendon architecture including structural and mechanical properties was summarized as a chart (Fig. 9.7) (Nordin and Frankel, 2012).

Tendon response to loading, injury, and healing

Physiological responses to mechanical loading and injury

Tendons connect muscle to bone and transmit forces to produce motion. Chronic and acute tendon injuries are very common and result in considerable pain and disability. The management of tendon injuries remains a challenge for clinicians. Effective treatments for tendon injuries are lacking because the understanding of tendon biology lags behind that of the other components of the musculoskeletal system. Animal and cellular models have been developed to study tendon-cell differentiation and tendon repair following injury. These studies have highlighted specific growth factors and transcription factors involved in tenogenesis during developmental and repair processes. Mechanical factors also seem to be essential for tendon development, homeostasis, and repair. Mechanical signals are transduced via molecular signaling pathways that trigger adaptive responses in the tendon. Understanding the links between the mechanical and biological parameters involved in tendon development, homeostasis and repair is prerequisite for the identification of effective treatments for chronic and acute tendon injuries (Nourissat et al., 2015).

Mechanical loading and adaptation concept

Tendons can adapt to changes in their mechanical environment due to loading, exercise, injury or disease. Thus, ligaments and tendons are an example of the structure-function concept and the mechanically mediated adaptation concept.

Mechanotransduction is an important mechanism for adaptation concept by which mechanical stress acts upon a cell and initiates intracellular signaling, promotes cell growth and survival, governs morphology and architecture, and influences metabolic responses (Kjaer, 2004). The term mechanotransduction can formally be defined as “the processes whereby cells convert physiological mechanical stimuli into biochemical responses” and it has a homeostatic role for maintaining normal musculoskeletal

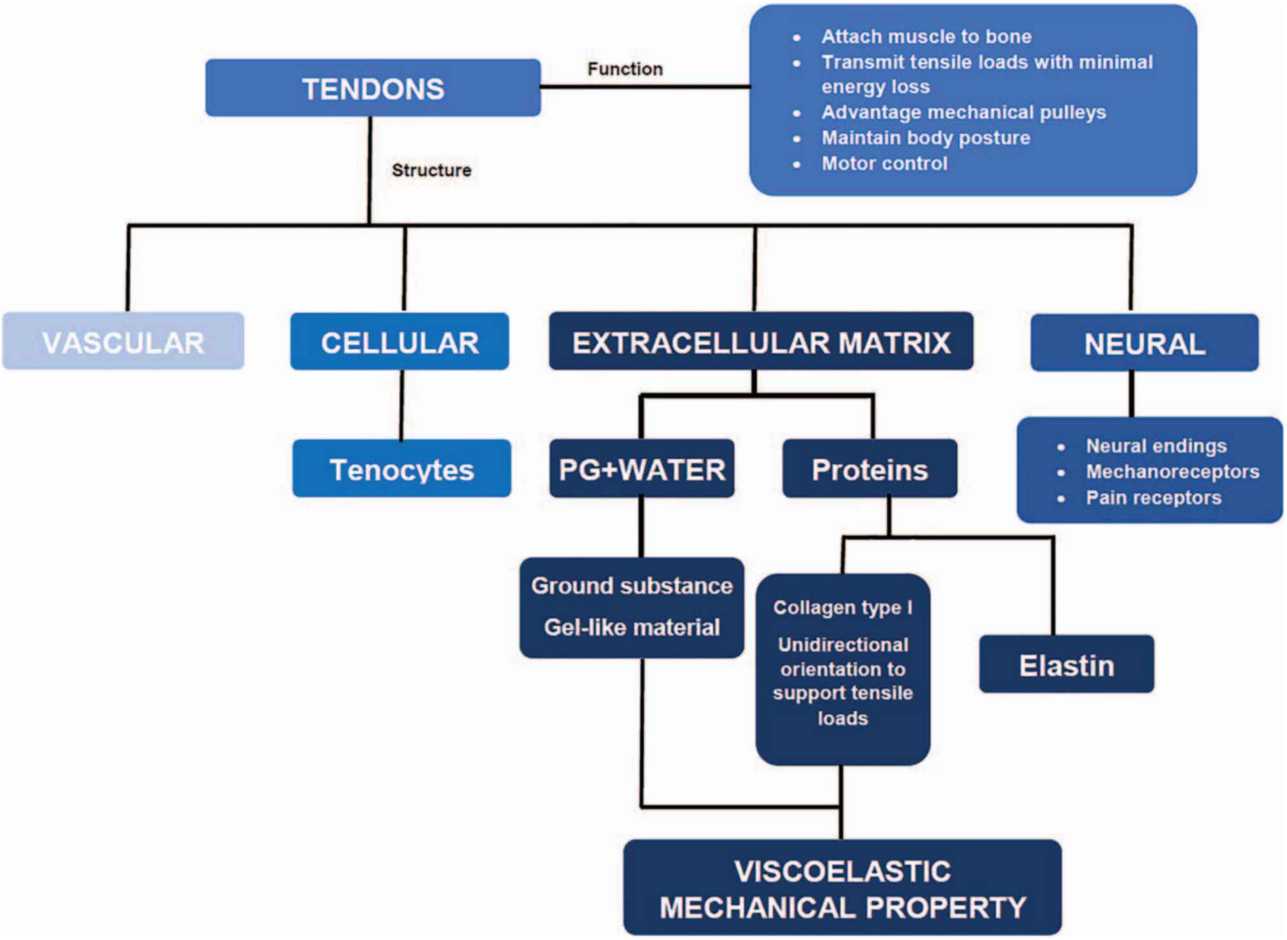

FIGURE 9.7 Tendon architecture summary.

structures in the absence of injury. In other words, the body converts mechanical loading into cellular responses and they promote structural changes. It is an ongoing physiological process in the human body (Khan and Scott, 2009).

Mechanotransduction is governed by the cytoskeleton, a network composed of filamentous biopolymers (actin microfilaments, microtubules, intermediate filaments) that mechanically stabilizes the cell and actively generates contractile forces (Ingber et al., 2014). Stretch-activated ion channels, caveolae, integrins, cadherins, growth factor receptors, myosin motors, cytoskeletal filaments, nuclei, ECM, and numerous other structures and signaling molecules have all been shown to contribute to the mechanotransduction response (Ingber, 2006). Integrin molecules are major structural components of adhesion complexes at the cell membrane linking the ECM to the cytoskeleton. In this way, integrins establish a mechanical continuum along which forces can be transmitted from the outside to the inside of the cell and vice versa. Integrins together with the cytoskeleton form a mechanically sensitive organelle (Ingber, 2000; Kjaer, 2004).

Mechanotransduction is broken down into three phases: 1) mechanocoupling (the mechanical trigger or catalyst), 2) cell-cell communication (the communication throughout a tissue to distribute the loading message), and 3) the effector response (the tissue “factory” that produces and assembles the necessary materials in the correct alignment). The communication at each stage occurs via cell signaling—an information network of messenger proteins, ion channels, and lipids. Mechanocoupling refers to shear or compressive load causing a physical perturbation to cells and it is transformed into a variety of chemical signals both within and among cells. In the second phase (cell-cell communication) the stimulus in one location leads to a distant cell registering a new signal even though the distant cell does not receive a mechanical stimulus. The signaling proteins include calcium and inositol triphosphate. At the last phase, mechanical loading stimulates protein synthesis at the tendon cell network for orientation. The integrin proteins that bridge the intracellular and extracellular regions, and the cytoskeleton, function to maintain cell integrity and distribute the mechanical load. With movement, the integrin proteins activate at least two distinct pathways. One involves the cytoskeleton that is in direct physical communication with the nucleus. Another pathway is a series of triggered biochemical signaling agents. After a series of intermediate steps, those biochemical signals also influence gene expression in the nucleus. Once the cell nucleus receives the appropriate signals, normal cellular processes are engaged. mRNA is transcribed and shuttled to the endoplasmic reticulum in the cell cytoplasm, where it is translated into protein. The protein is secreted and incorporated into ECM. Consequently, the mechanical stimulus on the outside of the cell promotes intracellular processes leading to matrix remodeling (Khan and Scott, 2009).

Tendon is a dynamic, mechanoresponsive tissue. One of the major load-induced responses shown both in vitro and in vivo in the tendon is an upregulation of insulin-like growth factor (IGF-I). This upregulation of IGF-I is associated with cellular proliferation and matrix remodeling within the tendon. The other growth factors and cytokines in addition to IGF-I are also likely to play a role. When a tendon is trying to heal, there is up-regulation of IGF-I, other growth factors, and cytokines which allows for cellular proliferation and tissue remodeling. Too much stress or too little stress on the tendon tissue may cause an alteration in the up-regulation in cellular level. It may not allow the tendon to heal optimally. Tendons respond positively to "controlled loading." Therefore, tendons need optimal loading with mechanotherapy. Researches focusing on the type and intensity of ideal controlled loading conditions and exercises for different types of the tendon (eccentrics, assisted, resisted) are still ongoing (Khan and Scott, 2009).

According to the current knowledge of tendon mechanobiology, the tensile pre-stress such as gravity in the cytoskeleton influences cellular response to mechanical stimulation and, therefore, to biochemical signals. The biochemical mediators modulate the mechanical properties of cells and their surrounding matrix, which in turn regulates cellular mechanosensitivity and responses to mechanical stimulation. A proposed mechanosensory protein complex beneath the plasma membrane comprised of integrin and actin binding partners represent a physical link in activation pathways to transduce strain or shear stress. The pathways that link to the deformation sensors often involve transient changes in intracellular concentration of calcium ([Ca2 +]i), which results in the activation of downstream pathways, such as PGE2 release as well as alterations in the expression of matrix genes (Lavagnino et al., 2015).

The entire bodies use "tensegrity" architecture via mechanotransduction to stabilize their shape and to integrate structure and function (Ingber, 1997). Tensegrity architecture is a building principle describing a class of discrete network structures that maintain their structural integrity because of tensile prestress in their cable-like structural members (Stamenovic and Ingber, 2002). Through the use of this tension-dependent building system, mechanical forces applied at the macroscale produce changes in biochemistry and gene expression within individual living cells. Tensegrity also provides a mechanism to focus mechanical energy on molecular transducers and to orchestrate and tune the cellular response. This structure-based system provides a basis to explain how the application of physical therapy applications might influence cell and tissue physiology (Ingber, 1997, 2008).

Individual components of the musculoskeletal system have also been viewed as biotensegrity structures. The principles of biotensegrity and the role of mechanotransduction in cell physiology lead one to consider the possibility of pathologic states due to altered mechanotransduction. Changes in the extracellular environment or within the cell may lead to altered mechanotransduction and ultimately result in disease (Swanson, 2013).

The human body has the ability to adapt to its ever-changing environment. The principles of biotensegrity provide an explanation as to how the body can receive constantly changing mechanical forces, disperse these forces throughout the organism, convert them into biochemical signals within the cell, and retain its structural integrity (Swanson, 2013).

Cells in mechanically active tissues detect, process, and relay load signals to surrounding cells in a feedback loop designed to provide tissue homeostasis. Tendon cells respond to load by activating ion channels, increasing $[Ca^{2+}]$, releasing ATP, altering their cytoplasmic filament organization and content (especially actin), and altering their protein expression and secreting metalloproteinases. Mechanical loading causes the release of ATP in almost every cell type, including tenocytes (Humphrey et al., 2014; Lavagnino et al., 2015).

In the absence of activity, the mechanotransduction signal is weak, so connective tissue is lost. When there are loads above the tissue's set point, there is a stimulus through mechanotransduction so that the body adapts by increasing protein synthesis and adding tissue where possible. Compressive loading leads to fibrocartilaginous metaplasia in tendons. Cyclic compressive hydrostatic stresses are a possible mechanical stimulus for fibrocartilaginous metaplasia in tendons. Cyclic hydrostatic pressures may stimulate changes in tendon cells toward a more chondrocytic phenotype, leading to increased synthesis of cartilaginous ECM components, including proteoglycans such as aggrecan. The resulting compositional changes lower the permeability of tissue in the fibrocartilaginous region. Decreased permeability allows the tissue to maintain fluid pressures for longer periods of time, reducing the compressive stresses and strains imposed on the solid constituents of the ECM. This adaptation enables tendons to function effectively for an entire lifetime without sustaining excessive mechanical damage due to cyclic compressive loading (Wren et al., 2000a,b).

Differences in the loading conditions may affect the adaptive responses. Following a period of enhanced mechanical loading, tendon stiffness may increase to maintain physiological ranges of strain during locomotion. Two mechanisms could account for an increase of tendon stiffness: 1) changes of the tendon material (i.e., increase of Young's modulus), and 2) changes of the tendon morphological properties (i.e., increase of cross-sectional area). Both tendon material and morphological changes result from an increase of collagen synthesis, changes of collagen fibril morphology and levels of collagen molecular cross-linking. The stiffness adaptation depends on loading conditions (e.g., intensity, duration of single loading cycle, repetitions, sets, intervention duration, and training frequency per week) and general exercise conditions (e.g., type of muscle contraction (isometric, concentric, or eccentric) applied repetitively or statically, differences in joint angles that affect the tendon lever arm length and, thus, acting stress on the tendon). High magnitude loading (i.e., muscle contraction intensity) is most effective to elicit tendon adaptation and that longer intervention durations (>12 weeks) are beneficial compared to shorter ones. The effect of muscle contraction type (isometric, concentric-eccentric, or isometric) seems insignificant (Chiquet et al., 2009; Bohm et al., 2015).

Tendon injury and pathology

The type and prevalence of tendon injuries are dependent on a number of factors including sex, age, levels of normal daily activity, overall health, and the circumstances contributing to the injury. Tendon impairments typically result from an internal tensile overloading event, with acute injuries occurring after one isolated, overloading event and chronic injuries occurring over time through repetitive, excessive loading events (Galloway et al., 2013).

Tendon injuries, categorized as chronic degenerative tendinopathies or acute ruptures, either alone or in combination. Degenerative tendinopathy often precedes acute ruptures, with the former considered a failed healing response that is characterized by hypervascularity, mucoid degeneration, ectopic bone, and cartilage nodules, and disorganized ECM (Yang et al., 2013).

Repetitive loading of human tendon tissue often leads to overuse injury (tendinopathy) that result in severe clinical symptomatology including pain, regional swelling, and soreness, decreased exercise tolerance of the tendon and a reduction in function. Characteristic changes occur in tendon structure, resulting in a tendon that is less capable of sustaining repeated tensile load (Cook and Purdam, 2009).

Tendon pathology and pain arise at the tendon attachment to bone or in the mid-tendon. While the mid-tendon and the insertion are morphologically different in the normal state, the onset of pathology appears to be the same. However, clinical outcomes and reflections to the loading in different parts of the tendon might be different.

The load has been shown to be both anabolic and catabolic for tendons. Repetitive energy storage and release and excessive compression appear to be key factors in the onset of tendinopathy. The amount of load (volume, intensity, frequency) that induces pathology is not clear; however, sufficient time between loadings to allow a tendon to respond to load appears important. Therefore, volume (hours) and frequency (sessions per day or week) of the intense load may be critical in the capacity of both normal and pathological tendons. Although load is a major pathoaetiologic component, it is almost certainly modulated by an interaction between intrinsic factors such as genes, age, circulating and local cytokine production, sex, biomechanics, and body composition. Tendon diseases may involve many different structures, might be seen at the different sites of the tendon with variable clinical findings (Table 9.1) (Heybeli et al., 2016). Tendinopathy and tendon rupture are discussed in detail below.

Tendinopathy

Tendinopathy is an umbrella term that indicates a non-rupture injury in the tendon or paratendon that is exacerbated by mechanical loading (Scott et al., 2015). In the late 1990s, Maffulli et al. advocated a shift in clinical terminology from tendinitis to tendinopathy. Both terms are typically used as generic descriptors for pain/swelling of an injured tendon, without distinguishing involvement of tendon versus paratendon or presence/absence of inflammation (Maffulli et al., 1998). However, terminology regarding tendon pathology has been confusing. The term tendinosis is used by some in preference to tendinitis to shift the focus away from inflammation. The term tenosynovitis refers specifically to the pathology of a fully developed synovial sheath (e.g., finger flexors/extensors), which typically presents with acute swelling with or without crepitus and triggering. Paratendonitis or peritendinitis describes the involvement of the paratendon, alone or in combination with tendinosis (Kaeding and Best, 2009; Scott et al., 2015).

Patients with tendinopathy display tendons that are thicker, but with reduced energy-storing capacity, meaning that for the same load, their tendons exhibit higher

TABLE 9.1 Tendon injuries and diseases.

Disease	Description	Example	Clinical findings
Tendinosis	Degeneration of tendon structure	Lateral epicondylitis, subacromial tendinosis	Pain, localized tenderness, nodule in palpation
Tenosynovitis	The disease of synovial sheath itself	De Quervain disease	Pain, tenderness, swelling of the sheath, crepitation, warmth (early term)
Stenosing tenosynovitis	The disease of tendon and synovial sheath	Trigger finger	Pain, crepitation, nodule on palpation, triggering in the finger
Paratenonitis	The disease of paratenon layer	Achilles paratenonitis	Pain, tenderness, swelling, crepitation, warmth (early term)
Enthesopathy	The problem in the attachment site of the tendon to the bone	Achilles tendinosis	Tenderness, swelling at the site of attachment to bone, pain
Rupture	Disruption in the integrity of a tendon (partial or complete)	Shoulder tendon rupture—Achilles rupture	Pain (may be absent), loss of strength, feeling of emptiness on palpation
Cytoskeletal contracture	Hardening of tendon sheath and attachment of it to the surrounding tissues	Cytoskeletal contracture or myofibroblast stiffness	Restrictions in joint mobility

strains than those of healthy individuals. This represents a decline in both the structural and material properties of the tendon tissue with reduced load-bearing capacity (Scott et al., 2015).

Tendinopathy is characterized by the gradual onset of morning stiffness in the tendon, decreased function, localized swelling, and sometimes neovascularization (Khan et al., 1999; Boesen et al., 2006; Fredberg and Stengaard-Pedersen, 2008). Normal tendons have low vascularity but have sufficient supply for their metabolic needs. In the pathologic tendon, increases in vascularity (neovascularization) has been demonstrated using Doppler ultrasound (Zanetti et al., 2003; Visnes et al., 2015) (Fig. 9.8). Neovascularization maybe associated with nerve fibers and also with pain (Woo et al., 2007). Pathologic tendons with neovascularization show more painful condition than without neovascularization (Cook et al., 2004). A significant increase in neovascularization and neoinnervation in calcific tendinitis lesions of the shoulder along with an eightfold increase in mast cells and macrophages was shown (Hackett et al., 2016). However, it was also declared that neovascularization might be observed in both a painful and non-painful tendons (van Snellenberg et al., 2007). The pain mechanism is partly unknown. Traditional theories state that pain arises through inflammation while others include biochemical stimulation of the nociceptors. Danielson et al. recently found that tenocytes produce acetylcholine. The nerve fibers showing immunoreactions for the acetylcholine-receptor M2 were observed in association with the small blood vessels in tendinopathy (Danielson et al., 2006). Prostaglandins,

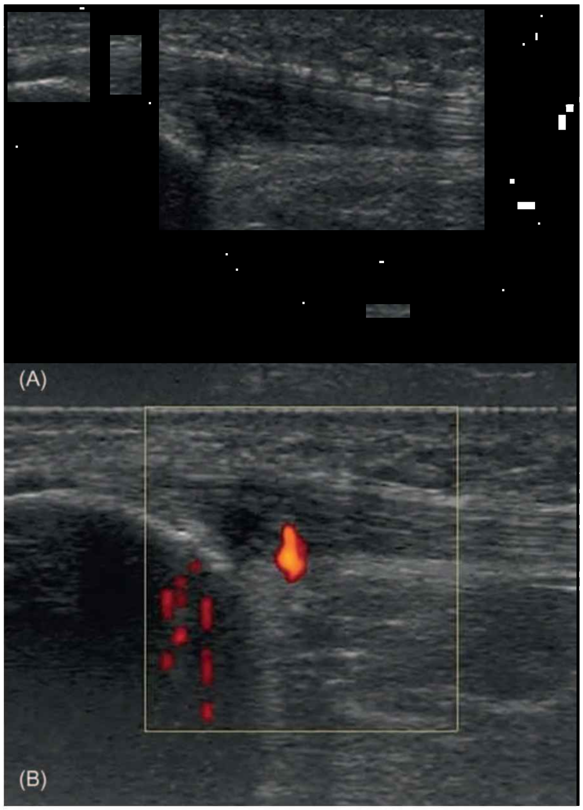

FIGURE 9.8 Sonographic and Doppler imaging of patellar tendinopathy, (A) thinning and hypoechogenicity in patellar tendon insertion, (B) tendon neovascularization. *With the permission from Ugur Toprak, MD.*

prostacyclins, and thromboxanes (prostanoids) contribute to the development of pain by acting both peripherally and centrally (Fredberg and Stengaard-Pedersen, 2008). Currently, investigations are increasingly focused on the nerve supply to the tendons. Nerve ingrowth is known to occur as a response to tendon injury. This new nerve ingrowth in the tendon accompanied with the blood vessels have been suggested as a potential origin of the pain in tendinopathy (Alfredson et al., 2003; Danielson et al., 2006; Fredberg and Stengaard-Pedersen, 2008; Ackermann et al., 2016). Furthermore, central nervous system-driven contributions were declared for tendon pain as well as local nociceptive contributions (Rio et al., 2014).

For the etiology of tendinopathy three main theories have been mentioned: Mechanical theory, vascular theory, and neural theory. According to the mechanical theory repeated loading within the normal physiological stress, range causes fatigue and eventually leads to tendon failure. As the tendon is loaded it passes through two stretch regions. The first (known as a toe stretch region) is due to the stretching out of the crimped structure. If stretching is continued past the toe region then the tendon enters a linear relationship between load and strain (Fig. 9.4) (Rees et al., 2006).

Tendons are metabolically active tissues requiring a vascular supply. According to vascular theory, compromise of this supply may cause degeneration (Fenwick et al., 2002). Under maximal tensile load, ischemia occurs on a tendon. After relaxation of the load, reperfusion occurs. It may create oxygen free radicals those may cause tendon damage resulting in tendinopathy (Bestwick and Maffulli, 2004; Sharma and Maffulli, 2005). Peroxiredoxin 5 is found in human tenocytes. Peroxiredoxin 5 is an antioxidant enzyme that protects cells against damage from reactive oxygen species. Its expression is increased in tendinopathy. Oxidative stress may play a role in inducing tenocyte apoptosis (Wang et al., 2001). The neural theory emphasizes the close association within tendons of nerve cell endings and mast cells. This raises the possibility of neurally mediated mast cell degranulation and release of mediators such as substance P (a nociceptive neurotransmitter) and calcitonin gene-related peptide. Chronic tendon overuse may, therefore, lead to excessive neural stimulation and result in mast cell degranulation (Rees et al., 2006). In addition to the theories, the genetic factors involving type V collagen A1, tenascin-C, matrix metalloproteinase−3, and estrogen-related receptor beta have been associated with tendon injury (Vaughn et al., 2017).

The chronic tendinopathy histopathology include the followings: a disorganization of collagen fibers, an increase in the number of vessels and sensory nerves, an increase in the hydrated components of the ECM, a breakdown of tissue (tendon/endotendon/paratendon) organization, haphazardly arranged proliferation of smaller type III collagen fibers, and a failure of cell-matrix adaptation (Scott et al., 2015; Buschmann 2017). There are frequently areas of cell death (eg, hypocellularity) or, alternatively, of fibroblast reaction (eg, hypercellularity and adhesions). It is typical to find both degenerative and reactive changes within the same biopsy, even in very severe, long-standing cases. It is also postulated that there is a resident population of fibroblast-like cells within tendons that, after injury, can differentiate into several lineages (osteoblast, chondrocyte, adipocyte, tenocyte), leading to metaplasia (eg, bony, cartilaginous, or adipocyte transformation) (Sharma and Maffulli, 2005; Cook and Purdam, 2009).

At the cellular level, increased numbers of leukocytes (especially macrophages and mast cells) and vascular cells in chronically painful tendons were observed. Macrophages with accumulations of hemosiderin (an indicator of prior injury that resulted in an activation of the innate immune response) in their cytoplasm are more prevalent in tendinopathic than in normal tendon. At a biochemical level, increased levels of glycosaminoglycan and inflammatory mediators such as substance P and prostaglandin E2 (PGE2) were declared. (Cook and Purdam, 2009; Scott et al., 2015).

Overuse tendon injuries; commonly involve the patellar tendon, Achilles tendon, the origin of the extensor carpi radialis brevis (tennis elbow), and rotator cuff tendinopathy of the musculoskeletal disorders (Xu and Murrell, 2008; Galloway et al., 2013; Abat et al., 2017). Excessive loading events lead to microtear formation in the tendon, which, if not repaired properly, may lead to the initiation of inflammatory and degenerative responses. This results in an overall weakened structure and increased propensity for tendon rupture (Buschmann, 2017). Tendinopathy has been described as a continuum of pathology with three distinct stages; reactive tendinopathy, tendon disrepair, and degenerative tendinopathy. There is continuity between stages (Cook and Purdam, 2009). Reactive tendinopathy is a non-inflammatory proliferative response in the tendon cell and matrix which occurs after acute overload from tensile or compressive forces. Tendon disrepair phase is categorized by the tendon's attempt at healing with greater matrix degradation. The increase in proteoglycans causes disorganization of the matrix and separation of the collagen. It alters the loading capacity of the tendon. Further progression of both matrix and cell changes with areas of cell death from apoptosis and trauma is called degenerative tendinopathy phase (Cook and Purdam, 2009).

Tendon rupture

Degenerative tendinopathy is the most common histological finding in spontaneous tendon ruptures. Arner et al.

reported degenerative changes in all of their seventy-four patients with an Achilles tendon rupture, and they hypothesized that those changes were due to intrinsic abnormalities that had been present before the rupture. Kannus and Jozsa found degenerative changes in 865 (97%) of 891 tendons that had spontaneously ruptured, whereas degenerative changes were seen in 149 (33%) of 445 control tendons. Tendon degeneration may lead to reduced tensile strength and a predisposition to rupture (Sharma and Maffulli, 2005). Similarly, supraspinatus tendon injuries may be seen after degenerative processes (Heybeli et al., 2016). Fig. 9.9 shows the different stages of tendon injury at supraspinatus tendon through the magnetic resonance imaging (MRI).

Both mechanical (strain and overload) and pathological (related to diseases such as thermal injuries, inherited disorders, corticosteroids, endocrinologic and metabolic diseases, rheumatoid arthritis, congenital diseases, infections, and tumors) injuries may affect and cause degenerations in tendon structure or even rupture tendons (Nordin and Frankel, 2012). They were summarized as a chart in Fig. 9.10.

Tendon healing

Following tendon injury, the natural healing process forms scar tissue via a three-overlapping phase: inflammation, proliferation (fibroblastic or matrix production), and remodeling (maturation) (Galloway et al., 2013; Docheva et al., 2015) (Fig. 9.11). The inflammatory phase initiates the response to injury, typically throughout the first week. It begins with the formation of hematoma after injury (Docheva et al., 2015). Erythrocytes and inflammatory cells, particularly neutrophils, enter the site of injury

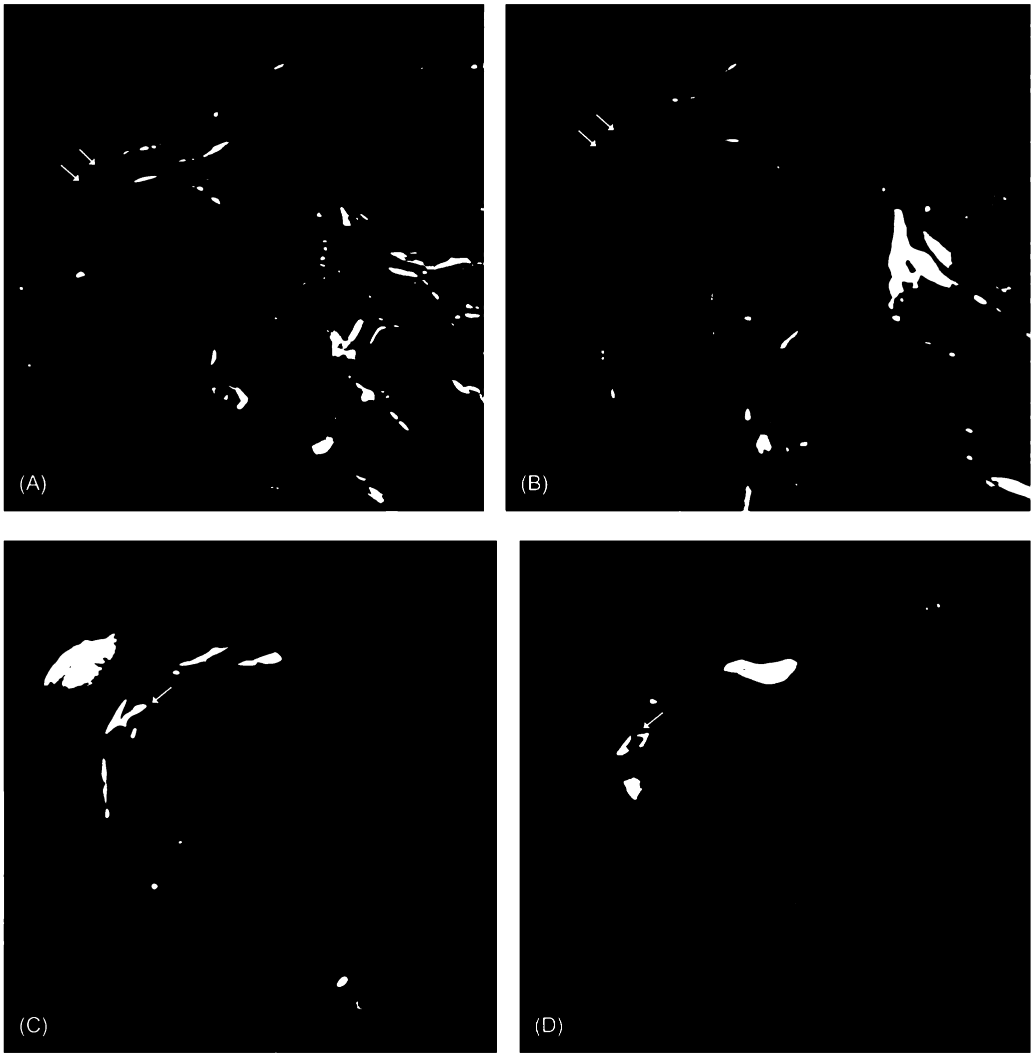

FIGURE 9.9 Shoulder MRI images of supraspinatus tendon; (A) normal healthy tendon, (B) tendinopathy related signals, (C) partial rupture with effusion of subdeltoid bursa, (D) complete rupture with effusion of subdeltoid bursa. *With the permission from Ugur Toprak, MD.*

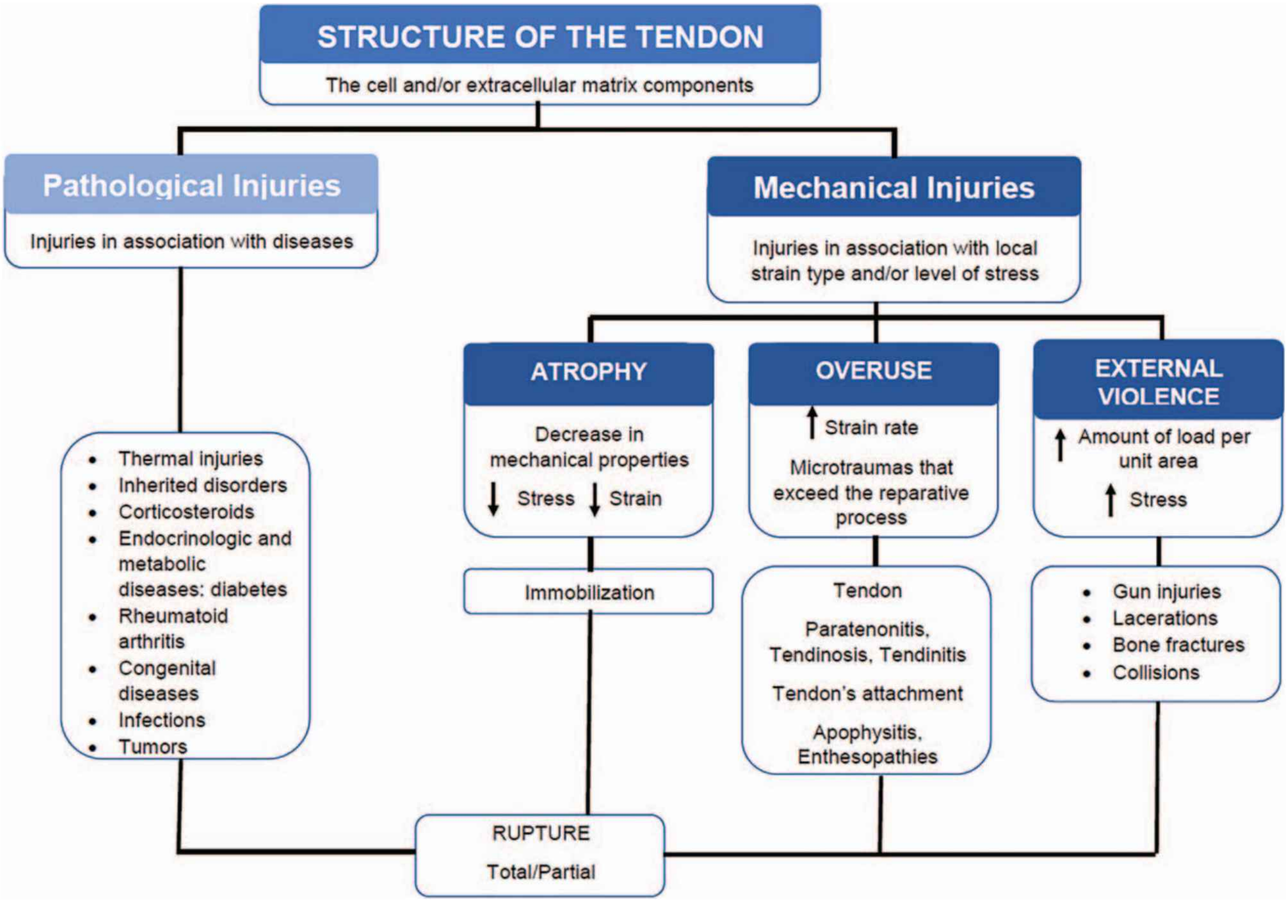
STRUCTURE OF THE TENDON
The cell and/or extracellular matrix components
Pathological Injuries
Injuries in association with diseases
Mechanical Injuries
Injuries in association with local strain type and/or level of stress
ATROPHY
Decrease in mechanical properties
↓ Stress ↓ Strain
OVERUSE
↑ Strain rate
Microtraumas that exceed the reparative process
EXTERNAL VIOLENCE
↑ Amount of load per unit area
↑ Stress
Thermal injuries
Inherited disorders
Corticosteroids
Endocrinologic and metabolic diseases: diabetes
Rheumatoid arthritis
Congenital diseases
Infections
Tumors
Immobilization
Tendon
Paratenonitis, Tendinosis, Tendinitis
Tendon's attachment
Apophysitis, Enthesopathies
Gun injuries
Lacerations
Bone fractures
Collisions
RUPTURE
Total/Partial

FIGURE 9.10 Chart for tendon injuries.

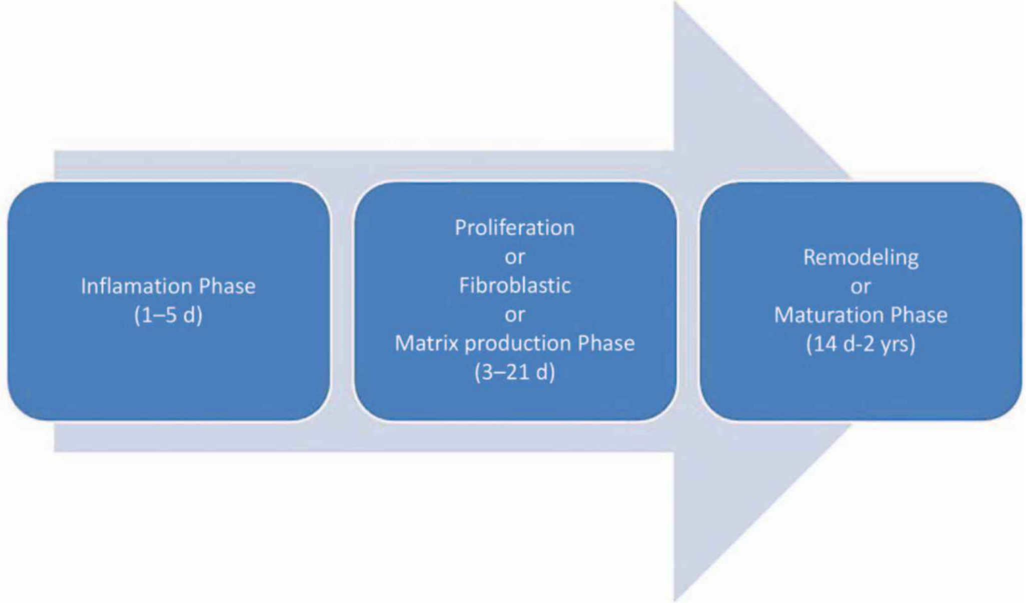

FIGURE 9.11 Tendon healing phases.

to stabilize it. In the first 24 hours, monocytes and macrophages predominate and phagocytosis of necrotic materials occurs. Vasoactive and chemotactic factors are released with increased vascular permeability, initiation of angiogenesis, stimulation of tenocyte proliferation, and recruitment of more inflammatory cells. Tenocytes gradually migrate to the wound, and type-III collagen synthesis is initiated. After a few days, the proliferative phase begins. Synthesis of type-III collagen peaks during this stage and lasts for a few weeks. Water content and glycosaminoglycan concentrations remain high during this stage. After approximately six weeks, the remodeling phase commences, with decreased cellularity and decreased collagen and glycosaminoglycan synthesis. The remodeling phase can be divided into a consolidation stage and a maturation stage. The consolidation stage begins at about six weeks and continues for up to ten weeks. In this period, the repair tissue changes from cellular to fibrous. Tenocyte metabolism remains high during this period, and tenocytes and collagen fibers become aligned in the direction of stress. A higher proportion of type-I collagen is synthesized during this stage. After ten weeks, the maturation stage occurs, with a gradual change of the fibrous tissue to scar-like tendon tissue over the course of one year. During the latter half of this stage, tenocyte metabolism and tendon vascularity decline (Galloway et al., 2013; Docheva et al., 2015; Thomopoulos et al., 2015)

There are two aspects of tendon healing that distinguish healing of this tissue from the healing of other tissues. The first is the tremendous tensile strength that must develop between the tendon ends. The second aspect is the development of a type of separation in the single scar such that the healed tendon can move or glide within the surrounding scar tissue (Sharma and Maffulli, 2006).

Tendons have support from local structures that aid the initial healing process by providing vascular supply and fibroblasts. These structures include the periosteum of underlying bone, the synovial sheath, the epitenon, and the endotenon. The specific tendon healing activities are summarized in Table 9.2 during healing timeline (Houglum, 2016).

One of the major limitations of tendon healing is the adhesion formation after intrasynovial tendon injury. Synovial sheath disruption at the time of injury or surgery allows granulation tissue and tenocytes from surrounding tissue to invade the repair site. Exogenous cells predominate over endogenous tenocytes, allowing the surrounding tissues to attach to the repair site resulting in adhesion formation. Despite remodeling, the biochemical and mechanical properties of healed tendon tissue may never match those of intact tendon. The absence of mechanical

TABLE 9.2 Tendon healing timeline.

Phase	Timing	The activity
Inflammation	First 3 d	Cells that originate from extrinsic peritendinous tissue and from intrinsic tissue from the epitenon and endotenon are active
	5 d	Wound gap is filled by phagocytes
	1 wk	Collagen synthesis is initiated, with new collagen fibers placed in a random and disorganized way
Proliferation	10 d	Collagen synthesis is maximum
	3 wk	The tendon provides significant fibroblast proliferation in the injury site. Significant revascularization occurs. Synovial sheath is reconstituted. The synovial sheath is rebuilt, and smooth gliding surface develops. Fibroblasts also start to become oriented in line with the tendons axis
	4 wk	Fibroblasts predominate in the healing area. Collagen content increases. Collagen is fully oriented with the tendons long axis
	35 d	Collagen synthesis is completed
	42 d	Fibroblasts that have proliferated from the endotenon are the primary cells, simultaneously synthesizing collagen while contributing to collagen resorption.
Remodeling	2 mo	Collagen is mature and realigned along the tendon's axis
	112 d	Fibroblasts have reverted to tenocytes, type III collagen has been replaced by type I, and maturation is complete
	40–50 wk	Strenght is 85–95% normal

loading during the period of immobilization might be the main reason (Sharma and Maffulli, 2006).

Optimal loading and rehabilitation

The primary goal of tendinopathy treatment is to obtain normal tendon development and homeostasis. Controlling the mechanical environment of healing tendon may exert a biologic effect through the mechanotransduction mechanism and holds promise for promoting a repair process that restores normal tendon structure and function (Chiquet et al., 2009; Nourissat et al., 2015). Many treatment methods including corticosteroid injections, nonsteroidal anti-inflammatory medications, physical therapy modalities (cryotherapy, ultrasound, iontophoresis and low-level laser therapy, shock wave therapy), manual therapy methods (deep friction massage, soft tissue massage), tendon needling and exercise-based rehabilitation (especially eccentric loading), sclerotherapy, nitric oxide patches, growth factors, platelet-rich plasma, stem cell treatment, and surgery have been mentioned and researched in the literature (Rees et al., 2006; Andres and Murrell, 2008; Joseph et al., 2012; Lui and Ng, 2013; Krey et al., 2015; Fitzpatrick et al., 2017). Optimal tendon loading has been a key factor to optimize healing and function (Galloway et al., 2013; Glasgow et al., 2015; Nourissat et al., 2015).

Optimal loading may be defined as the load applied to structures that maximize physiological adaptation, while also minimizing the negative outcomes (Glasgow et al., 2015). Because, intact tendons adapt slowly to changes in mechanical loading, whereas in healing tendons the effect of mechanical loading or its absence is dramatic (Andersson et al., 2009). Achieving optimal loading is challenging but should be driven by variables such as the tissue type, pathological presentation and the required issue adaptation for eventual activity. Specific loading goals may include increased tensile strength, collagen reorganization, increased muscle-tendon unit stiffness or neural reorganization. Optimal loading works through various cellular and neural mechanisms to induce a wide range of changes. Manipulation of loading variables can have profound effects on the nature, structure, and function of the wider neuromusculoskeletal system (Killian et al., 2012; Glasgow et al., 2015). Like other connective tissues (e.g. bone and muscles), tendons adapt to altered levels of load or physical activity. The mechanical stimulus is crucial for cell survival, growth and tissue-specific functions (Bring et al., 2007). Variable loading may be effective in three ways. First, small variations in the magnitude, direction, and rate of loading may serve to provide a degree of stress shielding of tissues from repetitive loading. Second, small variations in loading may promote a greater 'mechanotransductive' effect through broader stimulation of mechanoreceptors and prevention of accommodation; the phenomenon of accommodation is well recognized for a range of other stimuli such as temperature, pressure, and light. Finally, variable tensile, compressive and torsional forces may promote the creation of stronger biological scaffold that is better able to withstand a range of loading types (Galloway et al., 2013; Glasgow et al., 2015).

Physical activity speeds up tendon healing, which may prove to be linked to accelerated neuronal plasticity, (Bring et al., 2007) and the evidence that a high strain magnitude, an appropriate strain duration, and repetitive loading are essential components for an efficient adaptive stimulus for tendons (Bohm et al., 2014). The tissue has a "memory" of loading episodes and that therefore short loadings are sufficient to elicit improved healing. Once the tissue had received information from a certain loading type and level, this is "memorized" and leads to a response lasting many hours (Andersson et al., 2009). Therefore, for both chronic and acute tendon injuries, exercise-based rehabilitation is indicated (Khan and Scott, 2009; Nourissat et al., 2015). At the early reactive phase of tendon injury, high-load isometric contractions in positions that do not compress the insertion may relieve pain (Rio et al., 2015). Moreover, isometric contractions may be more analgesic than isotonic exercises (Rio et al., 2017). Conversely, high-load elastic or eccentric loading, particularly with little recovery time (eg, on successive days), will tend to aggravate tendons in this stage (Cook and Purdam, 2009). For late disrepair/degenerative phases, treatments that stimulate cell activity, increase protein production (collagen or ground substance) and restructure the matrix are appropriate. For more than 30 years, eccentric exercise has been presented as one of the best options to treat chronic tendinopathy (Abat et al., 2017). The concept of using eccentric exercise in tendon injury rehabilitation was introduced by Stanish et al. (Stanish et al., 1986) in the mid-1980s and Alfredson et al. (Alfredson et al., 1998) popularized it later on. Since then eccentric contractions have been shown to improve tendon structure in both the short term and the long term (Langberg et al., 2007; Woodley et al., 2007; Murtaugh and Ihm 2013; Abat et al., 2017). Eccentric exercises may cause changes in the metabolism of the tendon, which therefore result in altered pain perception. It creates temporary interruption of blood flow in the tendon neovessels (Rees et al., 2009). Eccentric training for 12-wk was shown a reduction of neovascularization (Ohberg and Alfredson, 2004), pathologically increased capillary blood flow without changes in tendon oxygen saturation (Knobloch, 2007), the abnormal paratendinous capillary blood flow in Achilles tendinopathy by as much as 45% and also decreased pain levels

(Knobloch et al., 2007). Rees et al. (2008) found that the tendon is subjected to repeated loading and unloading in a sinusoidal-type pattern during eccentric exercises, with high-frequency oscillations in tendon force. This was largely absent during concentric exercises. The pattern of tendon loading and unloading, with its force fluctuations, may provide an important stimulus for tendon remodeling and be responsible for the therapeutic benefit (Rees et al., 2008). Langberg et al. (2007) investigated the effect of eccentric exercises on collagen synthesis. Eccentric training was found to increase collagen synthesis, increase peritendinous Type I collagen.

Heavy slow resistance exercise was introduced as another good option for Achilles tendinopathy treatment since they might reduce pain and thickness and as well as neovascularization (Beyer et al., 2015). Tendon neuroplastic training has been another concept of strength-based loading that focused on strategies known to optimize neuroplasticity of the motor cortex for patellar tendinopathy (Rio et al., 2016).

Muscle activation can induce analgesia, improving self-efficacy associated with reducing one's own pain. Strength training is beneficial for tendon matrix structure, muscle properties, and limb biomechanics. Mechanical alterations in cells result in changes to extra cellular matrix organization, cytoskeletal organization, and gene transcription. Exercise-based rehabilitation strategies must balance the negative outcomes that can arise from immobilization (e.g., increased adhesions, retarded repair tissue maturation, and joint stiffness) with the negative outcomes that can arise from too much load. Furthermore, the particular anatomy and functional requirement of a given tendon repair must be considered when determining the optimal rehabilitation scenario (Thomopoulos et al., 2015). Therefore, exercise-based rehabilitation programs should be designed according to the tissue healing timeline and both rehabilitation and healing phases. Characteristics, clinical symptoms, and objectives of rehabilitation in relation to rehabilitation and healing phases are summarized in Table 9.3 (Kisner and Colby 2012).

TABLE 9.3 Characteristics of repair phases and relationship with clinical symptoms and rehabilitation phases.

Acute phase	Subacute phase	Chronic phase
Inflammation	**Proliferation**	**Remodeling**
Characteristics		
Vascular changes	Removal of stimuli	Connective tissue development
Cell and chemical release	Capillary development	Scar tissue contracture
Clot formation	Collagen formation	Scar remodeling
Phagocytosis	Tissue granulation	Regulation of collagen against stress
Removal of irritants	Fragile sensitive tissue	
Early fibroblastic activity		
Clinical symptoms		
Inflammation	Reduced inflammation	No inflammation
Pain (without resistance)	Pain (against resistance)	Pain (after resistance)
Rehabilitation		
Protection phase	**Controlled motion**	**Return to function**
Inflammation control	Improvement of healing	Improving scar uniformity, strength
Modalities	Creating mobile scar tissue	Functional independence
Selective rest	Exercise	Progressive stretching, strengthening
Immobilization		Functional activities
Provision of early recovery		Specific skills
Passive movement, massage		
Controlled muscle activity		
Isometric contractions		

Architecture of ligaments

Structure

Ligaments are primarily composed of collagen (mostly type I and some type III), elastin fibers, and proteoglycans. The primary building unit is called the tropocollagen molecule. Tropocollagen molecules are organized into long cross treated fibrils that are arranged into bundles to form fibers. Fibers are further grouped into bundles called fascicles which group together to form the ligament. It shows a similar hierarchical structure to tendon with the following order: collagen, microfibril, subfibril, fibril, fascicle and ligament (Fig. 9.2) (Nigg et al., 2000; Frank, 2004).

Composition and biochemical constituents

Ligaments are primarily composed of water, collagen, and various amino acids. Approximately two-thirds of total ligament mass can be attributed to water and one third can be attributed to solids (Frank, 2004). Collagen represents approximately 75% of the dry weight of ligaments, while the remaining 25% contains proteoglycans, elastin, and other proteins and glycoproteins. Type I collagen accounts for nearly 85% of the total collagen within ligaments and the remaining balance consists of types III, V, VI, XI, and XIV collagen. The collagen fibers appear to have a characteristic, specially designed cross-linked formation, which contributes to the incredible strength of ligaments. Under the microscope, the collagen bundles appear crimped along their length and it is believed that the crimping is present in relation to the loading capacity or tension applied to ligaments. With load-bearing, certain areas of the ligament uncrimp, which allows the ligament to elongate without sustaining structural damage. It appears that some fibers tighten or loosen depending on musculoskeletal positioning and applied forces, which supports the joint through various tensions and ranges of motion (Hauser and Dolan, 2011).

The ECM consists of ground substance and fibers. The ground substance is the nonfibrous component of the matrix and is made up of glycosaminoglycans and proteoglycans. These long chain molecules are linked to the collagen fibers to help form connective tissue. The ground substance facilitates tissue metabolism and provides support, shock absorption, and resiliency. It also decreases friction and attracts and binds water. The varying percentage of water-binding protein contained in the ground substance affects the hydration level of the tissue. The fibrous component of the matrix is primarily collagen fibers, with some elastin. This is the support framework and comprises 75–80% of the dry weight of tendons and ligaments. Collagen is the most abundant protein in the human body; its basic building blocks are amino acids, primarily proline, glycine, and lysine. Its amino acid chains assemble into long triple helix molecules by hydrogen bonding to oxygen radicals along the chains. Ligaments also contain elastin fibers. Some ligaments, such as the ligamentum flavum that connects the vertebrae in the spine, are highly elastic, containing twice as many elastin fibers as collagen fibers. Elastin is more compliant and more extensible than collagen. In ligament, it acts like a rubber band to return the ligament to its original length after the stress is removed. The matrix of ligaments also contains a small number of proteoglycans, which aid in the regulation of water movement within the tissue (Weintraub, 2003).

Water occupies the largest percentage of weight (and space) in all tissues (60%–80%). Almost two-thirds of the wet weights of a ligament are water. Water in ligaments may provide lubrication and assist in providing nutrients to cells within the ligaments. Additionally, the presence of water and its interaction with the proteoglycans influences the viscoelastic behavior of the tissue. A significant amount of this water is associated with the ground substance (Thornton et al., 2001; Martin et al., 2015).

Ligament cells (fibroblasts) vary in shape, size, and density throughout the tissue, but they are relatively sparse and tend to orient with the long axis of the ligament. (Weintraub, 2003). Fibroblast cells in normal ligaments may be capable of cell-to-cell communication allowing the coordination of cellular and metabolic processes throughout the tissue (Frank, 2004). Presumably, fibroblasts monitor their environment and in response to local stimuli produce proteins that help to maintain and repair the ligament tissue. Proteoglycans, also found in the extracellular matrix, store water and contribute to the viscoelastic properties of ligaments. These viscoelastic features allow ligaments to progressively lengthen when under tension and return to their original shape when the tension is removed. Ligaments are covered by a more vascular and cellular overlying layer called the epiligament, which is often indistinguishable from the actual ligament. The epiligament contains sensory and proprioceptive nerves with more nerves located closer to the bony ligament insertion sites (Frank, 2004; Hauser and Dolan, 2011).

Function

Ligaments, lying internal or external to the joint capsule in the skeletal system, attach one bone to another and therefore supply passive support, guide joint movement and maintain joint congruency. Ligaments are also found around other joints and along the spine. Outside the skeletal system, ligaments support internal organs and structures including the uterus, bladder, liver, breasts, and diaphragm. Ligaments are even found around teeth, connecting the teeth to the jaw bone. They function to supplement active stabilizers and bony geometry (Martin et al., 2015).

The fibers are generally oriented along the long axis of the ligament in order to resist tensile forces. However, some fibers align off-axis. Close to the points where the ligament inserts into a bone, the composition, and structure of the ligament changes so that it is stiffer, which may help to reduce the risk of tearing at the bone-ligament interface (Weintraub, 2003; Frank, 2004; Hauser and Dolan, 2011).

Ligaments also play a neurosensory role (Brand, 1989). They act as sensory organs and have significant input to sensation and reflexive/synergistic activation of muscles. When ligaments are strained, the proprioceptive nerves initiate neurological feedback signals that activate muscle contraction around the joint, which allows the body to protect and stabilize the joint after injury (Hauser and Dolan, 2011). It is hypothesized that injury to ligaments disrupts the neural apparatus as well as the structural support. Dysfunction following injury may result as much from neural injury as from structural instability. In some patients, "neural adaptation" likely occurs, while in others it does not (Brand, 1989; Solomonow, 2009).

Biomechanics and material properties

Ligaments are composite, anisotropic structures exhibiting non-linear time and history-dependent viscoelastic properties. The structural properties of isolated tendons, ligaments, and bone-ligament-bone preparations are normally determined via tensile tests. In such a test, a ligament, tendon, or bone-ligament-bone complex is subjected to a tensile load applied at a constant rate.

The term "load" refers to an external force applied to a structure. Two main factors determine the strength response of a ligament under loading: the size and shape, and the speed of loading. The greater the number of fibers that are oriented in the direction of loading, and the wider and thicker those fibers are, the stronger the ligament. These structures exhibit increased strength and stiffness (resistance to movement) with an increased speed of loading. A typical force-elongation curve obtained from a tensile test to a ligament. The force-elongation curve is initially upwardly concave, but the slope becomes nearly linear in the pre-failure phase of tensile loading. The force-elongation curve represents structural properties of the ligament. That is, the shape of the curve depends on the geometry of the specimen tested (e.g. tissue length and cross-sectional area). As the collagen fibers straighten, linearity develops, and in this relatively linear portion of the curve, the material's elastic (Young's) modulus can be measured. Elastic modulus is the slope of the linear region of the stress—strain curve. Near the latter part of the linear loading region, some of the collagen fibers may exceed their load-bearing capacity and rupture. If the load or stress removed at that point, there would be a partial failure, but the remaining intact fibers of the structure might still be able to carry out the load-transmission function. The partial tear may induce an inflammation response, and subsequent healing eventually will form scar tissue. If the tensile stress was increased even further, remaining fibers would fail (Fig. 9.3). If the tensile load is applied very quickly, it is more likely that the ligament will fail, whereas if the load is applied very slowly it is more likely that a piece of bone at the ligament attachment site will fail (avulsion fracture) (Whiting and Zernicke, 2008).

Vascular supply

Vascular supply to ligaments comes through the periarticular arterial plexuses. The extent of the vascular supply varies among ligaments and may depend on their location relative to the joint capsule. Intraligamentous vasculature is rather limited indicating that some degree of diffusion is necessary to supply the inner ligament fibers with needed nutrients. The vascularization to a ligament is important for the synthesis of new collagen. Microvascularity from insertion sites was obtained (Benjamin and Ralphs, 1997). Ligaments are covered by a more vascular and cellular overlying layer called the epiligament (Frank, 2004). The extent of vascular damage that occurs during ligament trauma is a significant factor affecting the ability of the ligament to heal itself. Ligament surgical and rehabilitative procedures should be designed to maintain or enhance the tissue's vascular supplies (Hauser and Dolan, 2011).

Neural structures

In addition to a vascular network, ligaments also contain a variety of neural elements. Nerves present within ligaments originate from nerves innervating muscles. Reflex pathways appear to exist which may allow ligament strain to be communicated to the central nervous system. The free nerve endings present in ligament are believed to detect joint position, speed, and movement direction. The epiligament includes sensory and proprioceptive nerves. These nerves travel in close proximity to the blood vessels with more nerves nearer to the bony ligament insertions. When ligaments are strained, the proprioceptive nerves initiate neurological feedback signals that activate muscle contraction around the joint, which allows the body to protect and stabilize the joint after injury (Frank, 2004; Hauser and Dolan, 2011).

Summary of ligament architecture

Ligament architecture including structural and functional properties was summarized as a chart (Fig. 9.12) (Nordin and Frankel, 2012).

Ligament response to loading, injury, and healing

Response to mechanical loading and injury

Ligament injuries are among the most common causes of musculoskeletal joint pain and disability. Knees, hips, shoulders, ankles, elbows, and wrists are among some of the joints most commonly affected by ligament injuries. The injuries create disruptions in the balance between joint mobility and stability, which can lead to abnormal transmission of forces throughout the joint, resulting in damage to other structures in and around the joint (Hauser and Dolan, 2011).

Ligament injuries can occur with direct or indirect mechanisms. The direct mechanism causes an injury secondary to trauma without a preexisting disease. With an indirect mechanism, there is a pathological degeneration process prior to the injury, as in tendons; and this process usually results from multifactorial causes. Mechanical compression, tensile overload, and compression can be counted among those causes (Heybeli et al., 2016). Ligaments exhibit nonlinear anisotropic mechanical behavior and under low loading conditions. Continued ligament-loading results in increasing stiffness until a stage is reached where it exhibits nearly linear stiffness and beyond this, then, ligament continue to absorb energy until tensile failure. Ligaments have "load relax" characteristic which means that loads/stresses decrease within the ligament if they are pulled to constant deformations. Ligaments also have "creep phenomenon" which is defined as the deformation (or elongation) under a constant or cyclically repetitive load. Creep is particularly important when considering a joint injury or reconstructive surgery as excessive creep could result in laxity of the joint thus predisposing it to further injury (Frank, 2004).

Ligaments are affected in accordance with the degree of injury in joint injuries. The injuries cause symptoms

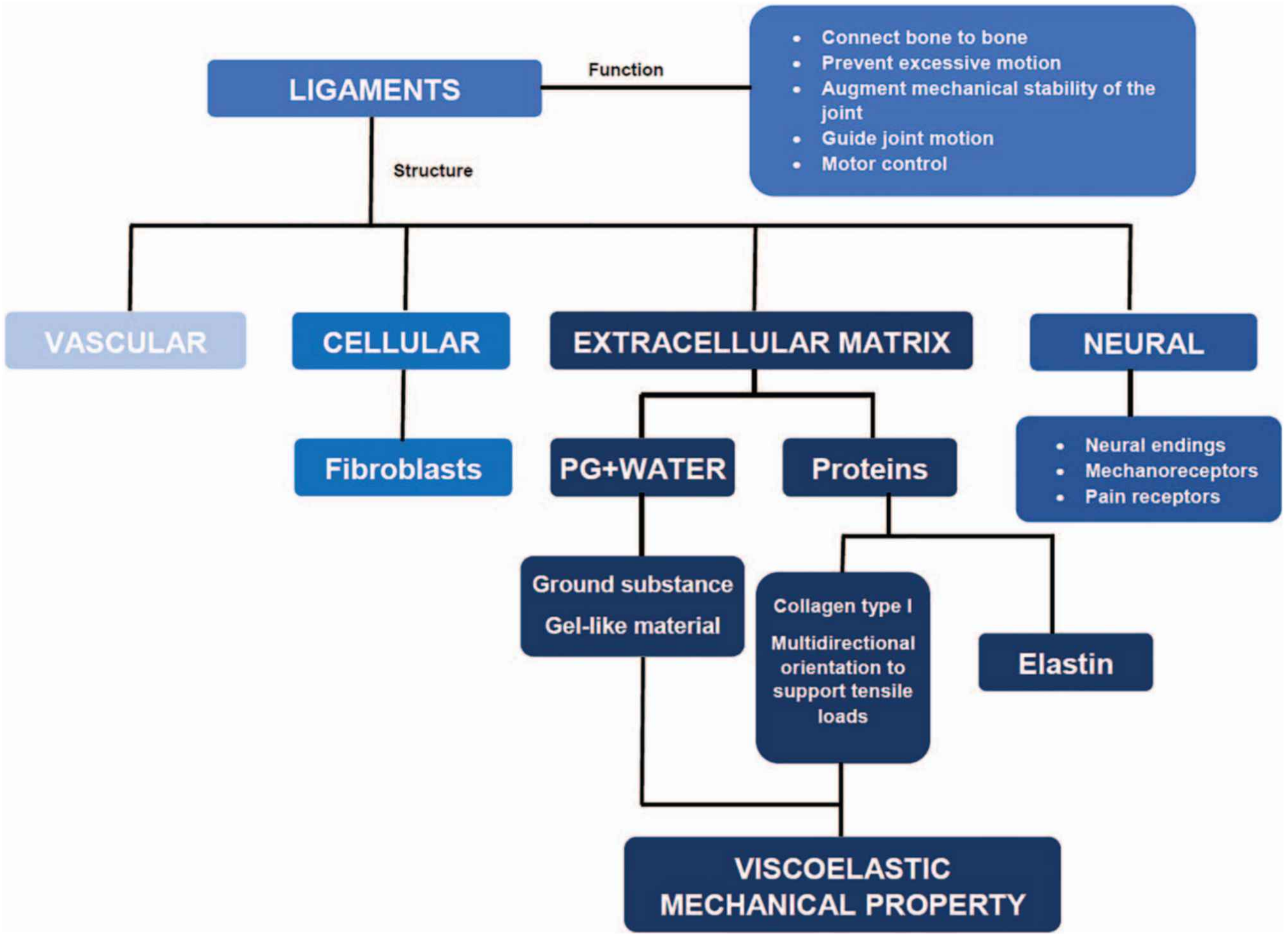

FIGURE 9.12 Ligament architecture summary.

depending on the affected part of the ligament, and can be classified into three degrees according to clinical severity. The first-degree sprain is the partial tear of a part of a functional band. Second-degree sprain has disruptions of many but not all fibers. However, some regions are undamaged. Lastly, in the third-degree sprain, the ligament injured completely, a total rupture (Heybeli et al., 2016). Moreover, failure could include ligament-bone units as well as ligamentous tissue. Three principal failure modes have been observed in ligament-bone preparations. The first type is a ligamentous failure, characteristic of fast loading rate failures. This failure mode results in a "mop end" appearance of the disrupted ligament ends. The bundles of fibers fail at different locations due to shear and tensile mechanisms between fibers. The second mode of failure is bony avulsion fracture, which occurs during slow loading rate failures. Failure occurs through cancellous bone beneath the insertion site. The third failure mode is cleavage (or pull-out) at the ligament-bone interface. This mode of failure is less common than the first two due to the efficient force dissipation that occurs through the insertional zone (Doschak and Zernicke, 2005).

With a ligament injury joint instability may occur, joint may subluxate, cause damage to the capsule, cartilage, tendons, nearby nerves and blood vessels, discs (if considering spinal joints) and to the ligaments themselves. Unstable joints may modify the intraarticular pressure, disrupt the muscular activity pattern around the joint, decrease joint proprioception and may further result in osteoarthritis, pain, disability and eventually the need for joint replacement surgery. Dysfunctional or ruptured ligaments, therefore, result in a complex syndrome, various sensory-motor disorders and other long-term consequences which impact the individual's well-being and activities (Solomonow, 2009). Furthermore, the incomplete healing and persisting differences in the new ligament tissue result in ligament laxity, which predisposes the joint to further injury. Ligament injury and subsequent laxity cause joint instability, which leads to chronic pain, diminished function, and ultimately osteoarthritis of the affected joint. Osteoarthritis continues to be the most common joint disorder as the long-term consequence of ligament injury (Hauser and Dolan, 2011).

Ligament healing

Tendons and ligaments heal in the same manner as other tissues following injury with the same three phases: the inflammatory phase, the proliferative phase or fibroplasia, and the remodeling and maturation phase. However, this process is slower for tendons and ligaments because of the limited vascularity of these tissues. The end result is the creation of scar tissue that is characterized by persistent flaws, abnormal ECM components, and the abnormally reduced diameter of collagen fibrils, which makes it biomechanically inferior to normal tissue. Although scar tissue can respond and adapt to load, it can improve to within only 10%–20% of normal tissue properties (Frank, 2004).

When a ligament is torn, frayed stump ends are present where the ligament has been separated. The ligament undergoes the inflammation process. The acute inflammatory phase begins within in minutes of injury and continues over the next 48–72 hours. The injured ligament stumps become surrounded with fluid. Local vascular permeability increases and permits normal inflammatory products and many cellular events occur. The proliferative/repair phase begins when immune cells release various growth factors and cytokines, which initiate fibroblast proliferation to rebuild the ligament tissue matrix. The tissue formed initially appears as disorganized scar tissue with more blood vessels, fat cells, fibroblastic and inflammatory cells than normal ligament tissue. Over the next several weeks, fibroblast cells deposit various types of collagen proteoglycans, other proteins, and glycoproteins to the matrix. The collagen becomes aligned with the long axis of the ligament during this time, however, the newly formed type of collagen fibrils are abnormal and smaller in diameter than normal ligament tissue. After a few weeks, the proliferative phase merges into the remodeling phase in which collagen maturation occurs for months to years after the initial injury (Frank, 2004; Hauser and Dolan, 2011). The specific ligament healing activities within healing phases are summarized in Table 9.4 (Houglum, 2016). With time, the tissue matrix starts to resemble normal ligament tissue; however, critical differences in matrix structure and function persist. The injured ligament structure is replaced with tissue that is roughly, histologically, biochemically, and biomechanically similar to scar tissue and remodeled scar tissue remains grossly, microscopically, and functionally different from normal tissues (Hauser and Dolan, 2011).

Different ligaments heal differently. There is variation in the ability of tendons and ligaments to heal. A good example is the medial collateral ligament of the knee, which can heal fully after total rupture without the need for surgical intervention; other ligaments, such as the anterior cruciate ligament, require grafting and reattachment following total rupture (Woo et al., 2000).

Nerve growth factor (NGF) and the brain-derived neurotrophic factor (BDNF) are factors mainly known for their regulation of central and peripheral neurons including axonal growth and neurotransmission. They were also identified as important features of tendon healing (Steyaert et al., 2006; Lykissas et al., 2007). Moreover, NGF is recognized as a strong promoter of ligament healing on structural, biochemical and molecular levels, partly

TABLE 9.4 Ligament healing timeline.

Phase	Timing	The activity
Inflammation	First few hours	The injury site fills with erythrocytes, leukocytes, and lymphocytes. The ligament stumps become progressively more friable with the accumulation of serous fluid in the area
	24 h	Monocytes and macrophages infiltrate the area. Fibroblasts begin to appear and eventually become significant in number
	48–72 h	Fibroblasts produce ECM
Proliferation	3–21 d	Proliferation begins
	1–2 wk	Fibrocytes and macrophages are numerous. Random collagen fibers and abundant ground substance are seen. Fragile vascular granulation tissue is seen at the injury site. The ECM continues to be synthesized by fibroblasts. Macrophages, mast cells, and fibroblasts continue to predominate. Vascular bunds appear in the wound to communicate with existing capillaries. Elastin is seen in the area
	2 d-6 wk	Proliferation phase occurs, during which cellular and matrix structure replace the blood cloth formed during exercise
Remodeling	14–21 d	Remodeling initiates
	6 wk-12 mo	Macrophages and fibroblasts diminish
	8 wk	Revascularization is complete
	Up to 12 mo	Collagen concentration stabilizes, with Tip I collagen replacing type III and collagen cross-links increasing in number. Ligament becomes more normal.
	40–50 wk	Near normal tensile strength is restored
	1–2 yrs	Healing is complete

by stimulation of angiogenesis and regulation of fibroblasts and myofibroblasts (Mammoto et al., 2008). The inflammatory mediators cyclooxygenase 1 and 2 (COX 1 and COX 2), inducible nitric oxide synthase (iNOS) and hypoxia-inducible factor-1α (HIF-1α) are also believed to contribute to tendon repair by enhancing the process from the inflammatory healing phase through to scar remodeling (Bring et al., 2010).

While there is a vast body of knowledge available regarding the structure and function of normal ligaments, understanding the structure and function of injured ligaments becomes more complicated due to the variability and unpredictable nature of ligament healing (Hauser and Dolan, 2011).

Optimal loading and rehabilitation

Controlling the healing process and optimizing loading are the main aims for ligament rehabilitation. Several strategies have been implemented to restore the properties of the injured ligament to preinjury status including, rest, mobilization, non-steroidal anti-inflammatory drugs, corticosteroid injections, and prolotherapy. While each of these therapies can help alleviate the subjective symptom of pain following ligament injury, they do not all necessarily contribute to the actual cellular repair and healing of ligament tissue. Traditionally, injured limbs have been treated with rest by splinting or casting. While immobilization of the affected joint has long been prescribed following ligament injury, it has since been discovered that healing ligaments are dramatically affected by the presence or absence of joint motion. The theory has been that rest or immobilization prevents further tissue damage in the joint by limiting its movement, and thereby, decreasing pain and swelling. It has also been thought that rest may help in improving recovery time, in decreasing functional impairment, and in reducing long-term pain. However, immobilizing a joint with a ligament injury can cause detrimental side effects, such as synovial adhesions, an increase in collagen degradation and a subsequent decrease in collagen synthesis, and a greater percentage of disorganized collagen fibrils (Hauser and Dolan, 2011). Protection and rest after injury are supported by interventions that stress shield, unload and/or prevent joint movement for various periods. However, short periods of unloading are required after acute soft tissue injury and aggressive ambulation or exercise should be avoided. But, rest should be of limited duration and restricted to immediately after trauma. Longer periods of unloading are harmful and produce adverse changes to tissue biomechanics and morphology. Immobilization causes ligament physiology to progressively switch from an anabolic to a more catabolic state. Progressive mechanical loading is more likely to restore the strength and morphological characteristics of collagenous tissue. Indeed, early mobilization with accelerated rehabilitation is effective after for ligament strains (Martinez et al., 2007; Bleakley et al., 2012).

Functional rehabilitation aligns well with the principles of mechanotherapy, whereby mechanical loading prompts cellular responses that promote tissue structural change. Mechanical loading upregulates mRNA expression for key proteins associated with soft tissue healing. The difficult clinical challenge is finding the balance between loading and unloading during tissue healing. If tissues are stressed too aggressively after injury, the mechanical insult may cause re-bleeding or further damage. Protection of vulnerable tissues, therefore, remains an important principle The secret is to find the 'optimal loading' (Khan and Scott, 2009; Bleakley et al., 2012).

Early controlled resumption of activity after injury, including repetitive loading on injured soft tissue structures such as ligaments and tendons, has profoundly beneficial effects including enhanced cellular synthetic and proliferative effects, increased strength, size, matrix organization and collagen content of ligaments and tendons. Mobilization has been shown to benefit the injured ligament by causing it to form more connective tissue, resulting in tissue that is stronger and stiffer than an immobilized counterpart. Motion causes an increase of blood flow to the affected joint, providing the damaged ligament tissue with nutrients and metabolites necessary for tissue repair and healing. Under loading conditions, cells within the ligament detect tissue strains and respond by modifying the tissue. Results of numerous animal studies have shown that the strength of repaired ligaments is greater in animals which were allowed to continue to exercise, rather than to rest (Thornton et al., 2003; Yang et al., 2013). Early motion and accelerated programs were introduced and shown to be successful for ligament rehabilitation after an injury or a surgery (Kaeding and Best, 2005; Beynnon et al., 2011; Galloway et al., 2013; Miyamoto et al., 2014).

Ligaments may be subject to changes in water content as a result of injury or as a result of treatments such as ligament reconstruction and joint immobilization. Changes in ligament water content may influence low-load viscoelastic behavior. Changes to viscoelastic behavior, especially creep (the increase in strain with the tissue under sustained or repeated stress) may, in turn, have important consequences for joint stability (Thornton et al., 2001).

High loads are a risk factor for the triggering of muscular hyperexcitability and the associated acute inflammation in the viscoelastic tissues when compared to lighter static and cyclic loads applied at the same work/rest schedule. Cyclic loading seems to be more deleterious to the viscoelastic tissues compared to static loading, as it triggers delayed muscular hyper-excitability at moderate and high loads, whereas static loading triggers it only at high loads (Solomonow, 2009).

Healing response of ligaments to any injury can be affected by several factors including age, genetics of patient, hormonal effects, the presence of any comorbidity, and mechanical and biological quality of the tissue prior to injury and changes in neurovascular structure. Gender-specific and hormone-related variables and ligament injuries potentially affect the response to both these injuries. Genetic factors are more common in some breeds than others like pathological scarring and keloid formation as playing a role in wound healing. The presence of comorbidity, which leads to impaired inflammatory response and wound healing response due to the increase of growth factors, may also affect the results of healing. Neural and vascular elements are likely to play an important role in the result of the healing process. Indeed, some ligaments that have more angiogenesis capability and resulting in providing more blood, heal better than others by joints' proprioception, nociception, and vasoregulation (Heybeli et al., 2016).

Comparison of tendons and ligaments

Tendons and ligaments have unique histological and biochemical characteristics, despite their gross similarities. First of all, they have different functions with similar structures. Tendon connects muscle to bone and it provides joint movement but ligament connects bone to bone and produces joint stability. In addition, ligaments act like a sensory organ (Moshiri and Oryan, 2013). Secondly, they both are mainly made up of collagen type I molecules and these molecules are arranged as fibrils, fibers, fiber bundles, and fascicles. However, ligaments contain slightly less total collagen than tendons and more glycosaminoglycans (Amiel et al., 1984). Thirdly, the metabolic activity of both structures are low when compared to other tissues (e.g. cartilage and bone), however, ligaments are more metabolically active than tendons, having more plump cellular nuclei, higher DNA content, larger amounts of reducible cross-links, and the presence of more type III collagen, as compared with tendons (Amiel et al., 1984; Moshiri and Oryan, 2013). Moreover, tendons have three different areas including tendon proper which is completely tendinous in nature, musculotendinous junction and finally the tendon to a bone junction which has three areas of bone, cartilage, and tendon. Ligaments have two different areas including the ligament part and bony attachments. In the bony attachment site, there are different parts including ligament fibers, Sharpey's fibers, cartilage, and bone. Therefore healing of tendons and ligaments are different based on the above-mentioned areas (Moshiri and Oryan, 2013; Martin et al., 2015). Tendon and ligament structures, mechanical properties, and common function were summarized in Fig. 9.13 (Nordin and Frankel, 2012).

Affecting factors for the architectures of tendons and ligaments

The most common factors and pathologies that affect the tendon and ligament are considered as aging, gender, hormones, estrogen deficiency, and pregnancy, immobilization, mobilization, exercise and sporting activities, comorbidities (diabetes mellitus, connective tissue disorders, renal disease), and pharmacologic agents (steroids, nonsteroidal anti-inflammatory drugs or NSAIDs) (Frizziero et al., 2016). Moreover, reconstruction and tissue engineering have gained popularity and impact on tendon and ligament injuries.

Aging

Material and structural properties of the tendon increase from birth through maturity and then decrease from maturity through old age. Aging changes the biology, vascular and compositional properties that alter their mechanotransduction, healing capacity, and biomechanical function of tendons and ligaments and results in common clinical pathologies. The mature athlete faces challenges associated with age-dependent changes in the rotator cuff, Achilles tendon, lateral humeral epicondylar tendons, quadriceps tendon, and patellar tendon. The anterior cruciate ligament and the medial collateral ligament are the most studied intra-articular and extra-articular ligaments, and both are associated with age-dependent changes in the literature (McCarthy and Hannafin, 2014). Funakoshi

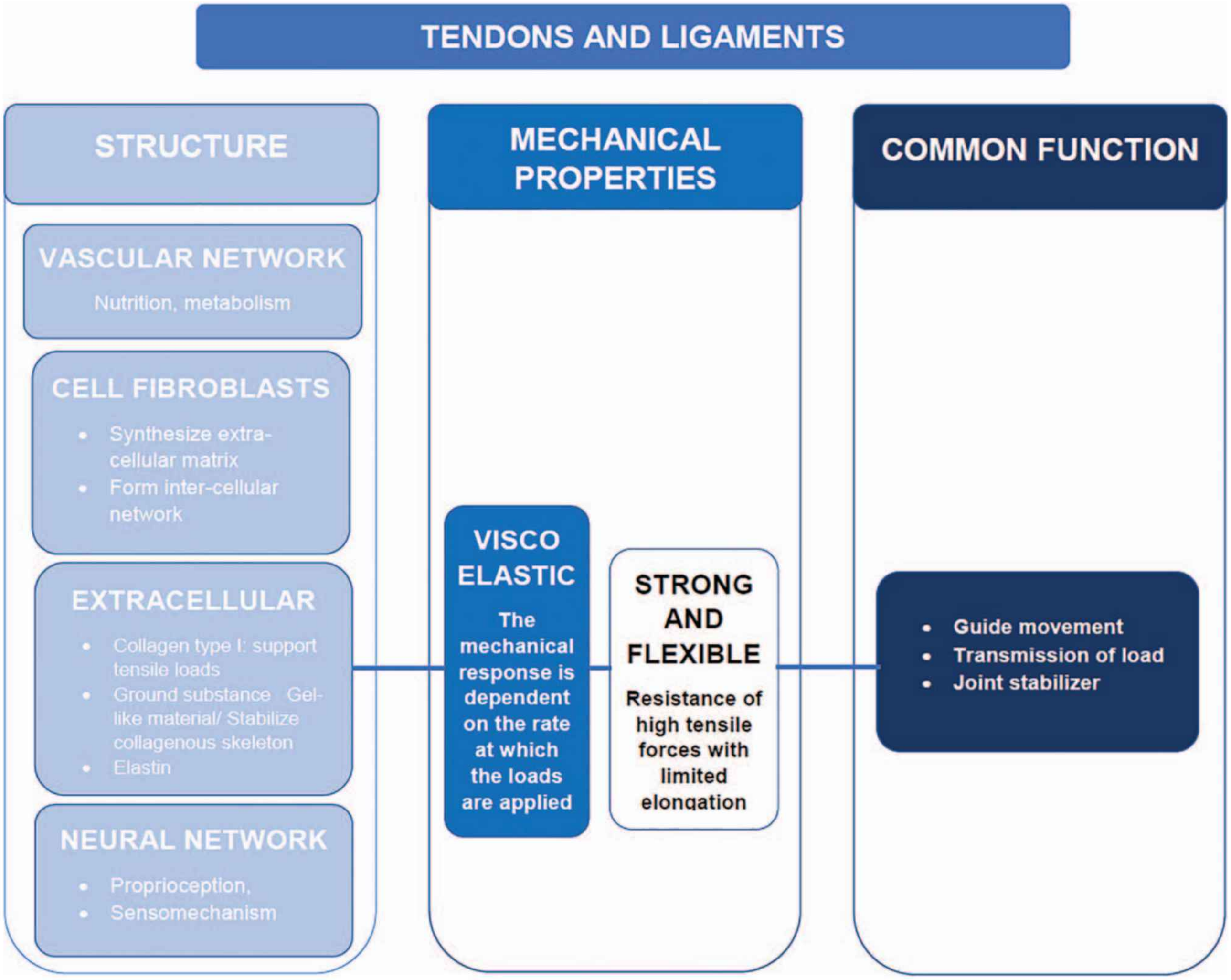
TENDONS AND LIGAMENTS
STRUCTURE
VASCULAR NETWORK
Nutrition, metabolism
CELL FIBROBLASTS
• Synthesize extra-cellular matrix
• Form inter-cellular network
EXTRACELLULAR
• Collagen type I: support tensile loads
• Ground substance Gel-like material/ Stabilize collagenous skeleton
• Elastin
NEURAL NETWORK
• Proprioception,
• Sensomechanism
MECHANICAL PROPERTIES
VISCO ELASTIC
The mechanical response is dependent on the rate at which the loads are applied
STRONG AND FLEXIBLE
Resistance of high tensile forces with limited elongation
COMMON FUNCTION
• Guide movement
• Transmission of load
• Joint stabilizer

FIGURE 9.13 Tendon and ligament structures, mechanical properties, and common function summary.

et al. (2010) evaluated the vascularity of rotator cuff tears using ultrasound and they showed that there was a significant decrease in blood flow in the intratendinous region in elderly subjects compared with younger subjects. However, no difference in the bursal blood flow suggesting an age-related decrease in intratendinous vascularity was observed. Rudzki et al. (2008) found a significant decrease in blood flow in the supraspinatus tendon in patients older than age 40 years compared with younger patients after exercise. Adler et al. (2008) also suggested a trend toward decreased blood flow with increasing patient age for the rotator cuff tendon. Thus the common sites of clinical tendon degeneration with age show significantly altered tendon vascularity (McCarthy and Hannafin, 2014).

In addition to vascular changes in tendon and ligament, mechanobiologic environment changes such as an increase in the degradative enzyme production in aging may also be observed. Matrix metalloproteinase-1 increase which is associated with significant reductions in the tensile modulus and tensile strength of tendons (Fu et al., 2002; Riley et al., 2002; Cook et al., 2016; Thampatty and Wang, 2017), increase in the number of apoptotic cells, overstimulation or under-stimulation which both may cause apoptosis (Arnoczky et al., 2007) occur.

In vivo studies, it was shown that with aging, rabbit tendon tissue extracellular matrix volume increases and the relative number of cells per unit of tendon decreases (Couppe et al., 2017). The tenocytes become longer and thinner and have decreased protein synthesis. The collagen fibers become more disoriented with more variations in thickness due to an increase in collagen, a decrease in mucopolysaccharides, and a decrease in water content. A significant decrease in total glycosaminoglycan, chondroitin sulfate, and dermatan sulfate with age in the supraspinatus tendon was also showed (Svensson et al., 2016; Fang and Lake, 2017). Aging is associated with a decreased potential for cell proliferation and a reduction in the number of stem/progenitor-like cells. Age correlates with a decrease in the number of tenoblasts and overall tenoblastic activity. Structurally, collagen fibers increase in diameter, vary in thickness, lose tensile strength, and become tougher with increasing age and so the ultimate tensile strength of a human tendon decline. The most characteristic age-related microscopic and biochemical pathological changes are degeneration of the tenocytes and collagen fibers, and accumulation of lipids, ground substance (glycosaminoglycans), and calcium deposits (Maffulli et al., 2005). The turnover in the core of the tendon after maturity is very slow or absent. Tendon fibril diameter, collagen content, and whole tendon size appear to be largely unchanged with aging, while glycation-derived cross-links increase substantially. Mechanically, aging was associated with a reduction in modulus and strength. With respect to exercise, tendon cells respond by producing growth factors, and there is some support for a loading-induced increase in tendon collagen synthesis in humans, which likely reflects synthesis at the very periphery of the tendon rather than the core. In addition, it seems that resistance training can yield increased stiffness and modulus of the tendon. A long-term exercise program tends to counteract, minimize and retard the effects of the aging tendon (Maffulli et al., 2005; Svensson et al., 2016; Buschmann, 2017).

Gender and hormones

The risk of overuse and traumatic tendon and ligament injuries differ between women and men. Part of this gender difference in injury risk is explained by sex hormonal differences. In women, a physiological high concentration of estrogen may enhance the risk of injuries due to reduced fibrillar crosslinking and enhanced joint laxity (Hansen, 2016). The presence of estrogen receptors in tenocytes has been demonstrated in human and animals (Bridgeman et al., 2010). These findings may indicate that tenocytes are influenced by estrogen level. The reduction of blood estrogen level is associated with a reduction in tensile strength, decrease in collagen synthesis, fiber diameter, density and increase degradation in tendon tissue (Frizziero et al., 2014). Furthermore, it was declared that estrogen-like compound might influence the stiffness, failure load, collagen content, and fibroblast proliferation in tendons. However, it is not sufficiently been described yet (Leblanc et al., 2017; Hansen, 2017).

Estrogen-like compound and other steroid hormones have a positive effect on the healing process of the skin through stimulation of local fibroblasts, however, the results on whether these findings translate to tendons and ligaments are conflicting (Leblanc et al., 2017). In men, testosterone can enhance tendon stiffness due to an enhanced tendon collagen turnover and collagen content, but testosterone has also been linked to reduced responsiveness to relaxin (Hansen, 2016).

Relaxin is a hormone reported to affect collagen synthesis. Its effects are also thought to be modulated by other sex hormones, including estrogen, which has previously been found to be associated with alterations of in vivo tendon properties. There is thus a potential for relaxin to impact on collagen, which could result in tendon structural and mechanical properties being modified. In young, normally menstruating women, relaxin appears to have a significant effect on the patellar but not the gastrocnemius tendon stiffness (Pearson et al., 2011). A common clinical observation is the increased laxity of the tendons and ligaments in the pubic area during later stages of pregnancy and the postpartum period that is attributed to the hormone relaxin. The stiffness of these structures decreased in the early postpartum period but was later restored (Nordin and Frankel, 2012).

Thyroid hormones, in particular, T3 and T4 play an antiapoptotic role on tenocytes, causing an increase in vital tenocytes isolated from tendons in vitro and a reduction of apoptotic ones; they are also able to influence extracellular matrix proteins secretion in vitro from tenocytes, enhancing collagen production (Oliva et al., 2013, 2016a,b).

Immobilization, disuse and exercise effects

Appropriate mechanical loads are useful to tendons by improving their anabolic processes and it is prescribed for different reasons such as sports performance, general health, functional maintenance, recovery (e.g., following injury, illness/diseased states) and also to compensate the effects of aging. However, extreme mechanical loads are harmful to tendons by bringing catabolic processes such as matrix degradation. Immobilization or disuse of tendons also leads catabolic effects on it (Frizziero et al., 2016). Prolonged immobilization following musculoskeletal injury often results in detrimental effects (Bring et al., 2010). Immobilization reduces the water and proteoglycan content of tendons and increases the number of reducible collagen cross-links. Immobilization results in tendon atrophy, but, due to low metabolic rate and vascularity, these changes occur slowly (Sharma and Maffulli, 2006).

In mature animals, immobilization does not lead to changes in weight or collagen content of tendons and ligaments, however, it affects collagen turnover such as cross-sectional area, modulus, strength, and stiffness. With remobilization tendons and ligaments recover their structural and material properties. It was declared that immobilized ligaments fail to increase dry weight, show less increase in stiffness (Wren et al., 2000a,b).

Plasticity of skeletal muscle is observed in humans under conditions of prolonged disuse that it can have a sizable negative effect on the mechanical properties of human tendons. In one study, mechanical unloading-induced by 90 days of bed rest reduced the gastrocnemius tendon stiffness by 60%; stiffness was measured as the slope of a force-elongation graph constructed using ultrasound-based recordings of tendon elongation during isometric ankle plantar flexion of graded intensity (Reeves et al., 2005). The tendon length and cross-sectional area remained unaltered after bed rest, so the Young modulus of the tendon (stiffness normalized to tendon dimensions), which reflects the material properties of the tendon, decreased also by approximately 60% as a result of bed rest (Narici and Maganaris, 2007).

All examined studies, both preclinical and clinical, observed that discontinuing activity negatively influence tendon structure and morphology. The results of all these studies suggested that after a period of sudden detraining (such as after an injury) physical activity should be restarted with caution and with appropriate rehabilitation programs because cessation of activity causes modifications in tenocytes and tendons metabolism, morphology, such as in collagen type I and III syntheses, collagen organization, cellularity, vascularity, proteoglycan content, tear density, mechanical properties (Frizziero et al., 2016).

Under normal exercise conditions, fibril stretching activates subcellular biology, releasing growth factors and triggering the subsequent synthesis of extracellular matrix components, predominantly proteoglycans, and collagen neofibrils. Homeostasis is maintained by the simultaneous production of appropriate metalloproteinases, which counteracts the anabolic effects of growth factors. When fibril stretching is increased but remains within the physiological window, synthesis prevails over degradation and tendon hypertrophy occurs (Heinemeier and Kjaer, 2011; Parkinson et al., 2011).

Tendons are designed to withstand considerable loads. Mechanical loading of tendon tissue results in upregulation of collagen expression and increased synthesis of collagen protein, the extent of which is probably regulated by the strain experienced by the resident fibroblasts (tenocytes). This increase in collagen formation peaks around 24 hours after exercise and remains elevated for about 3 days. The degradation of collagen proteins also rises after exercise but seems to peak earlier than the synthesis. Despite the ability of tendons to adapt to loading, repetitive use often results in injuries, which is characterized by pain during activity, localized tenderness upon palpation, swelling and impaired performance. Tendon histological changes include reduced numbers and rounding of fibroblasts, increased content of proteoglycans, glycosaminoglycans and water, hypervascularization and disorganized collagen fibrils. At the molecular level, the levels of mRNA for type I and III collagens, proteoglycans, angiogenic factors, stress and regenerative proteins and proteolytic enzymes are increased. Tendon microrupture and material fatigue have been suggested as possible injury mechanisms, thus implying that one or more ‘weak links’ are present in the structure (Magnusson et al., 2010).

For the cyclically loaded specimens, secant modulus decreased and cyclic energy dissipation increased over time (Wren et al., 2003). The increased concentrations of TGF-β, bFGF, and PDGF after cyclical mechanical stretching may have a positive influence on tendon and ligament healing through stimulation of cell proliferation, differentiation and matrix formation (Skutek et al., 2001). Strength training in old age increases the stiffness and Young’s modulus of human tendons. This may reduce the risk of tendon injury in old age and has implications for contractile force production and the rapid execution of motor tasks (Reeves et al., 2003).

Obesity

Obesity is characterized by an adverse biochemical milieu, and a chronic low-grade inflammatory state, which may predispose to tendon degeneration. It was shown that, in obese subjects, tendons frequently undergo degeneration, which can progress to a symptomatic stage, with pain and functional impairment (Abate, 2014). Adiposity may contribute to tendon disorders via two different mechanisms: increased weight on the load-bearing tendons and systemic dysmetabolic factors that trigger subclinical persistent inflammation (Abate et al., 2013). The main histopathologic findings are a relative paucity of small collagen fibrils, expression of an impaired remodeling process, deposition of lipid droplets which can abut to tendolipomatosis, and a disorganized architecture in the tension regions. Both load-bearing and non load-bearing tendons can be affected. This suggests that systemic factors play an important pathogenetic role. Indeed, adipose tissue releases several bioactive peptides and hormones (chemerin, lipocalin, leptin, and adiponectin), and cytokines responsible for a systemic state of chronic low-grade inflammation. Physical activity is strongly recommended to stop the progression of weight gain or to bring an obese individual into the normal weight range. Therefore, leisure sports activity is useful in obese subjects, but caution is mandatory, because tendons with subclinical damage, when submitted to overload, can easily reach the symptomatic threshold (Wearing et al., 2006; Abate et al., 2012; Abate, 2014).

Diabetes mellitus

In diabetes, the prevalence of rheumatological diseases is high. Diabetes mellitus is an important risk/causative factor for tendinopathies (Lui, 2017). The increased prevalence of several conditions such as Dupuytren's disease, trigger finger, carpal tunnel syndrome, and shoulder adhesive capsulitis have been reported in patients with diabetes. Poor glycaemic control has deleterious effects on advanced glycation end products that they deteriorate the biological and mechanical functions of tendons and ligaments. Their key characteristic is to form a covalent cross-link within collagen fibers, altering their structure and functionality (Abate et al., 2013; Snedeker and Gautieri, 2014). The excessive accumulation of advanced glycation end means the altered inflammatory response, neovascularization and intensitive neuropathy. Tendon stem/progenitor cells have been discovered to play important roles in both tendon physiology and tendon pathology (Shi et al., 2015). High glucose could inhibit cell proliferation, induce cell apoptosis and suppress the tendon-related markers expression of tendon stem/progenitor cells in vitro (Lin et al., 2017).

Hypercholesterolemia

Heterozygous familial hypercholesterolemia is caused by a defect in the catabolism of low-density lipoprotein (LDL), usually resulting from the inheritance of a mutant LDL receptor gene. Most patients develop tendon xanthoma, mainly in the Achilles tendon. It has been hypothesized that microscopic cholesterol deposition inside the tendons could initiate and maintain a low-grade, persistent inflammation; this, in turn, may be responsible for chronic tendon degeneration and biomechanical changes (Abate et al., 2013; Hast et al., 2014). Chung et al. concluded that hypercholesterolemia had a deleterious effect on fatty infiltration and the quality of tendon-to-bone repair site, and lowering hypercholesterolemia seemed to halt or reverse these harmful effects in the experimental model (Chung et al., 2016).

Hyperuricemia

Monosodium urate monohydrate (MSU) crystal depositions in joints (cartilage, synovial membranes, and tendons) and in other soft tissues are hallmarks of chronic gouty arthritis. Chronic cumulative urate crystal deposition leads to tophi formation. Tophi are usually walled off, but microtrauma-related changes in the size and packing of the crystal may loosen tophi from the organic matrix. This activity leads to crystal shedding and facilitates crystal interaction with residential inflammatory cells, leading to an acute gouty flare. A variety of inflammatory mediators, such as IL-1β, chemokines, and PGs, are released. A number of factors have been identified to explain the self-resolution of the acute attack: crystal dissolution or coating with proteins, neutrophil apoptosis, the inactivation of inflammatory mediators and the release of anti-inflammatory mediators. As for cholesterol, it is highly probable that the microscopic deposition of MSU crystals can occur in tendons, followed by low-grade persistent inflammation that causes chronic tendon degeneration (Abate et al., 2013; Andia and Abate, 2016).

Renal disease

Tendinous failure resulting from chronic renal failure does occur, with tendon rupture reaching 36% among individuals receiving hemodialysis. Hyperlaxity of tendons and ligaments was found in 74%, patellar tendon elongation in 49%, and articular hypermobility in 51% of individuals receiving long-term hemodialysis. Dialysis-related amyloidosis may cause the deposit of amyloid in the synovium of tendons. An increase in the amount of elastin and collagen destruction has also been suggested (Nordin and Frankel, 2012).

Connective tissue disorders

Connective tissue disorders such as rheumatologic conditions (e.g., rheumatoid arthritis, spondyloarthropathies) have been associated with inflammatory infiltrate that promotes the destruction of collagenous tissue. In addition, genetically inherited conditions (e.g., Marfan syndrome, Ehlers-Danlos syndrome) can result in deficiencies in the amount or the type of collagen present in tendons and ligaments, abnormalities in fibril structure, and an imbalance in the amount of elastin and other proteins altering its biomechanical properties (Riley, 2004; Nordin and Frankel, 2012).

Pharmacologic agents

Systemic intake of medications that include steroids, nonsteroidal anti-inflammatory drugs, and other medications such as fluoroquinolones can influence tendon and ligament metabolism.

Steroids. There is conflicting evidence regarding the short- and long-term effect of steroids on tendons and ligaments. However, they have been associated with the inhibition of collagen synthesis and the subsequently altered healing and a decrease in the peak load of these tissues. It was declared that despite the effectiveness of corticosteroid injections in the short term, non-corticosteroid injections might be of benefit (Coombes et al., 2010; Dean et al., 2014).

Platelet-Rich Plasma. Platelet-rich plasma (PRP) is derived from centrifuging whole blood, has a platelet concentration higher than that of the whole blood, is the cellular component of plasma that settles after centrifugation, and contains numerous growth factors. There is increasing interest in the sports medicine and athletic community about providing endogenous growth factors directly to the injury site, using autologous blood products such as PRP, to potentially facilitate healing and earlier return to the sport after musculoskeletal injury (Paoloni et al., 2011). PRP use in tendon and ligament injuries has several potential advantages, including faster recovery and, possibly, a reduction in recurrence, with no adverse reactions described. However, only 3 randomized clinical trials have been conducted (Redler et al., 2011; Taylor et al., 2011). However, the apparent benefit of PRP dissipates over time (Dragoo et al., 2014).

Fluoroquinolones. Fluoroquinolones are highly effective broad-spectrum antibiotics. Clinical data reveal an increased incidence of tendon pain and rupture in those taking it. Intake of fluoroquinolones has been found to cause an increase in the activity of matrix metalloproteinases, which therefore promotes the increased degradation of collagen (Stinner et al., 2010; Lewis and Cook, 2014; Lang et al., 2017).

Nonsteroidal Anti-inflammatory Drugs (NSAIDs). NSAIDs are widely used in the treatment of inflammatory diseases as well as of tendon diseases associated with pain in sports and labor. There is some evidence supporting their effectiveness in the treatment of inflammatory disorders of the tendons and ligaments (Christensen et al., 2011; Chen and Dragoo, 2013). The study of Christensen et al. (Christensen et al., 2011) demonstrated that intake of NSAID decreased interstitial PGE2 and abolished the exercise-induced adaptive increase in collagen synthesis in human tendons.

Reconstruction and tissue engineering

Reconstruction of ligaments whether using tendons as ligaments or other ligaments or graft materials by carrying out repair or replacement of parts is quite common treatment method in orthopedic medicine. Tissue engineering is defined as "a process that affects the structure and architecture of any viable and nonviable tissue with the aim to increase the effectiveness of the construct in biologic environments". Functional tissue engineering aims to produce a functional tissue replacement to repair defects. It involves the development of in vivo functional design parameters to fabricate engineered tissues which is an essential step toward the clinical application to promote repair outcome. Basically, tissue engineering could be divided into four major categories including tissue scaffolds, healing promotive factors, stem cells and gene therapy (Moshiri and Oryan, 2013; Chan et al., 2015). The developments about this area are enormous and it may alter tissue healing and adaptation in combination with new rehabilitation techniques.

Conclusion

Tendons and ligaments play a significant role for joint function and overall musculoskeletal biomechanics. Without them to stabilize and animate the skeleton would be mechanically useless. Therefore, they are common sites of musculoskeletal injuries caused by overuse, trauma, or diseases and their injuries are a significant burden to healthcare. Knowing the architectural characteristics, similarities and differences, adaptation abilities to loading, injury, and healing of tendons and ligaments may help to create effective treatment methods.

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Chapter 10

Architecture of fascia and its adaptation to pathological conditions

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Introduction

There are different definitions about fascia. “Fascia” is from Latin root, meaning bundle, strap, bandage, and binding together. In the First International Fascia Research Congress, 2007 in Berlin, fascia was defined as a “soft tissue component of the connective tissue system that permeates the human body” (Findley, 2009). The fascia is also defined as a “the fascial system consists of the three-dimensional continuum of soft, collagen containing, loose and dense fibrous connective tissues that permeate the body” by Fascia Nomenclature Committee (Bordoni and White, 2018), an as “masses of connective tissue large enough to be visible to the unaided eye” by Gray’s Anatomy (Standring, 2016). Its’ structure is highly variable. Although collagen fibers are seen parallel orientation at tendons and aponeuroses, collagen fibers tend towards each other in fascia. However, it has uncommonly intensive construction according to tendons and aponeuroses (Standring, 2016).

All the tissues of the body such as organs, muscles, nerves, and muscles fibers covered by fascia that creates a continuous tensional network while cartilage and bones, which do not create tension on fascia, are not defined as parts of tensional network in the fascia (Schleip et al., 2012). Additionally, fascia are in the dura mater, the periosteum, perineurium, the fibrous capsular layer of vertebral discs, organ capsules as well as in bronchial connective tissue, and the mesentery of the abdomen. There are some characteristic functions of fascia. These are like as force transmission, tissue repair, proprioception, and nociception.

Fascia

Fascia has three layers, which are called superficial, deep, and subserous fascia (Fig. 10.1). The superficial fascia is a flabby tissue under the skin (Bordoni and Whitte, 2018). The superficial fascia includes fat, capillary system, lymphatic channels, and nervous tissues. Nervous tissues consist of skin receptors like as pacinian corpuscles. The superficial fascia should be moved easily to all directions over the deep structure. Deep fascia is a dense, thick, and different fibrous connective tissue that interpenetrates and surrounds the muscles, nerves, and blood vessels under the superficial fascia (Bordoni and Whitte, 2018; Findley et al., 2012; Greenman, 1996). Microscopically, deep fascia is seen like as a firmly packed honeycomb (Lancerotto et al., 2011). The deep fascia is kept under basal tension with many muscular enlargements (Findley et al., 2012). Therefore, deep fascia causes the stimulation of proprioceptors by transmitting the tension of muscle contraction towards neighboring regions (Stecco et al., 2007). The peritoneum, pericardium, and pleura are

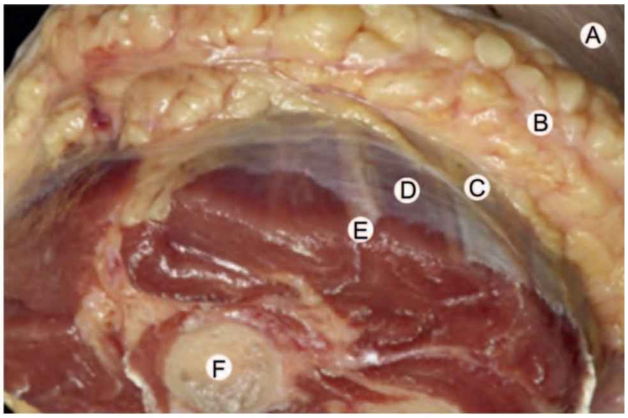

FIGURE 10.1 Fascial continuity from the skin up to the bone. A = Skin; B = ‘Honey comb’ fascia with the fat nodules; C = Superficial fascia; D = Deep fascia; E = Intermuscular septa; F = Bone (Schleip et al., 2012).

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specialized parts of this fascia. Compartment syndrome, which a painful condition is occurred at strong membrane, which is called deep fascia. Surgical fasciotomy might be needed to relieve nerve structure from compression. Subserous fascia covers the visceral organs and it is the loose areolar tissue (Greenman, 1996).

Whole body is covered the fascia which is interrelatedness. It could be called fascial chain or fascial trains. Upper and lower extremities are covered by deep fascia, and fascias at extremities are connected with thoracolumbar fascia. Connection between the thoracolumbar fascia, muscles, and other connective tissues are important categorizing as specific muscles at arm, spine, or leg. In transferring forces between spine, pelvis, and legs, thoracolumbar fascia plays a crucial role to transfer forces cranially, caudally, and diagonally. Consequently, understanding the fascia is important to solve complaints of patient, and to plan rehabilitation program (Schleip et al., 2012).

Biomechanics of fascia

Fascia has distinctive connective tissue architecture that differs from muscle to muscle. Yu et al. (2007) demonstrated fascia transfers the force of the muscle contraction. They found that during the activation of flexor pollicis longus was occurred about 5% of force, it was transferred to the index finger without any time delay. The results of this study supported that there are a viscoelastic mechanical connection between the muscles through the fascia. On the other hand, loading on the index finger could be as a result of and/or effected from neural synchronization with co-contraction of the muscles rather than direct force transmission (Yu et al., 2007).

The elasticity of the fascia ensures to retain its original shape during muscles contraction and relaxation (Greenman, 1996), so that fascia can adapt to mechanical stress (Bordoni and Whitte, 2018). However, if the applied force higher than the capacity of the fascia for a long time, fascia cannot turn back to original shape, which is called plastic deformation. Additionally, fascia has the creep capacity. When the fascia is exposed the extension load for a long time, this capacity could be changed. If the force is re-applied, fascia resists less than the first. This phenomenon is important for explaining of acute and repetitive injuries (Greenman, 1996).

Function of fascia

The fascia could be passive while it is very active organ. The aim of the fascia is to support the body parts, to provide stability by passing mechanical forces via lateral cross-links, to absorption stress, to strength movements, to provide lubricating fluid, and to give information about neuromuscular system. The function of the fascia depends on its location (Greenman, 1996; Klingler et al., 2014).

The fascia is a relaxed, wavy, quite flexible, able to resist tension, inseparable, and interconnection with their line (Bordoni and Whitte, 2018; Stecco et al., 2016) without injury/pathology/surgery. It allows to slide the muscular structure, nerves and vessels (Bordoni and Whitte, 2018). In case of trauma or inflammation, fascia should lose its softness and be more intense. The muscles spindles and fascia remain in touch and not move easily. Therefore, this strict relationship can cause joint pain, restricted range of motion, disrupted motor coordination, and decreased blood flow in case of injury/pathology/surgery (Stecco et al., 2016). Disrupted motor coordination is seen because the muscle spindles are strongly attached to the fascia (Von and Andres, 1994). Additionally, there are some specialized mechanoreceptors which are responsible for proprioceptors (Free Nerve Endings, Pacini-Rufini Corpuscles and Golgi-Mazzoni) at the fascia. These mechanoreceptors carry an information to central nervous system about movement and posture (Greenman, 1996).

Deep fascia surrounds and divides compartments to the body. After muscle contraction, the pressure of inside of the compartment increases to help efficiency of other muscles contractility within compartment (Panny et al., 2009). These changes of the pressure assist returning of venous circulation, and perfusion of the muscle (Nadland et al., 2009) such as calf muscles. Additionally, the proper placement of the collagen fibers in the superficial fascia can help the lymphatic circulation flow in the correct direction. Fibrosis of the superficial fascia can restrict capillarization and to break skin vascularization. When the arteriovenous shunts become deficient, thermoregulation is broken and excessively hot or cold skin is exposed (Stecco et al., 2016).

Another role of the fascia that has many sensory receptors are to carry sensory information. It is important to regulate perfusion and metabolism of organs. Perfusion and metabolism can be affected by dysfunction of fascia and as a result, capacity of regeneration can reduce (Schleip et al., 2012).

Effect of fascia on emotion

Emotion can be affected by the dysfunction of fascia during daily movements. Myofascial changes result in postural changes and as a result emotion is affected. The myofascial system is always innervated. All receptors into / around the fascia are responsible for proprioceptive, nociceptive, and interoception. These senses project to the brainstem, the autonomic and medullary centers, and thalamocortical extension. Any changes of these senses can affect the exteroceptive representations of the body such as pain tolerance, body image, and emotionality (Bordoni and Whitte, 2018).

Interoception is described as sense of the physiological condition of the body (Schleip et al., 2012). Interoception is triggered by free nerve endings and it gives information into insular cortex (Berlucchi and Aglioti, 2010) while no activation in the primary somatosensory cortex (Olausson et al., 2010). Examples of interoceptive sensations are warmth, coolness, muscular activity, pain, tickle, itch, hunger, thirst, vasomotor activity, sexual arousal etc. (Schleip et al., 2012).

Effect of surgery on fascia

Generally, biomechanics and functions of fascia are adversely affected by surgery. Scars tissue develops between fascial layers, inflammation could be seen around the fascia that causes adhesions and triggered the widespread pain. A prolonged inflammatory phase can result in proliferative scarring and increased fibrosis within the damaged area after surgery. Therefore, sliding between fascia layers can also negatively affected (reduce or stop). (Bordoni and Whitte, 2018). Velocity and/or perception of receptors (sensory/mechano/proprio) of the fascia are adversely affected by scar tissue due to the fact that capacity of regeneration can reduce (Schleip et al., 2012).

The surgical approaches depend on anatomical location and tissue thickness of injury/pathology. If the skin breaks down, the implant will be uncovered and attempted to cover it by mobilizing local tissue. If possible, skin incisions should be planned over muscles. In case of skin damage with underlying muscle exposed, this can be covered by a skin graft (Choi et al., 2018; Haumont et al., 2007).

Location of the vessels, nerves, and lymphatics is important to protect circulation, nutrition, and movement. To protect layers of the facia is also important to prevent adhesions. Additionally, it is very important to tip to tip the edges of the injured layers of the fascia properly.

All treatments such as rehabilitation and/or surgical should be respectful to soft tissue. In other words, it should be avoided hard treatment approaches of fascia tissue.

The role of fascia in proprioception

Proprioception is defined the ability to sense the position, location, orientation, and movement of the body and its parts. Proprioceptive mechanoreceptors and concerned afferent neurons are considered to provide the centripetal information needed for the control of locomotion or for the maintenance of posture. The mechanoreceptive information required for proprioception is due to the fascia and other connective tissue structures and the skin, muscles, joint surfaces and joint structures (Fig. 10.2).

Connective tissue continuity of fasciae and fascial structures serves as a mechanosensitive information system. This system is an integrate with nervous system (Langevin, 2006). Fasciae and fascial structures play a critical role in the process of proprioception (Langevin, 2006; Benjamin, 2009). Membrane, septa, or deep and superficial fascia are a complex part of locomotor function. To understand that function, the fascial structure should be equipped with sufficient neuroanatomical 'proprioceptors'.

Proprioception in the fascia is not only supplied by the mechanoreceptors, but also the architecture of the fascia plays an instrumental role in the process of proprioception. Schleip (2003a,b) refers the fascia as "the dense irregular connective tissue that surrounds and connects every muscle, even the tiniest myofibril, and every single organ of the body forming continuity throughout the

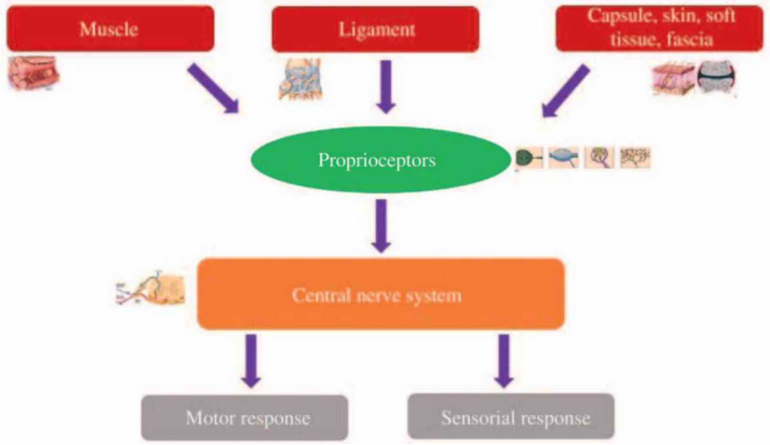

FIGURE 10.2 Summary of the proprioception mechanism.

body" or as the "organ of form" (Varela and Frenk, 1987). He actually presents fascia as an important integrative element in human posture and organization of movement. The mechanoreceptors in the muscle can direct the force transfer of the muscle to the fascial layers.

In order to play a functional role, proprioceptors do not have to be located within the facial fibers. Regarded mechanically, the intermediate zones between fascial dense connective from a mechanical point of view, the regions between the facial connective tissue and the connected muscle fibers may be the mechanoreceptive sensory source. In areas where the fascial connective tissue is so dense that it allows little dislocation or deformation, as is the case in most ligamentous structures, it seems logical that the innervation is more involved in nociception or sympathetic vascular regulation. As a result, the facial architecture plays an instrumental role in the process of proprioception without the need to equip the connective tissue directly with mechanoreceptors (van der Wal, 2009).

Fascial pathologies

Hypermobility

Stiffness is defined as the rigidity of an object the extent to which it resists deformation in response to an applied force. Stiffness can cause or contribute to myofascial pain. Facial stiffness usually occurs in several contractures associated with inflammatory processes (Klingler et al., 2014).

Hypermobility is a lack of stiffness that commonly associates with the soft tissue pain without conforming to anatomical details. This pain tends to be resistant to even strong analgesics, including opiates. Pain can be increased by active movement and related with kinesiophobia. Therapeutic approaches for hypermobility include exercises for core and joint stability. Proprioceptive exercises, pain management techniques, cognitive behavioral therapy, and general aerobic program are given to improve muscle strength, to decrease pain and kinesiophobia (Klingler et al., 2014).

Fascia-related disorders result from changed stiffness or compliance of the fascia. Compliance can be defined the opposite of stiffness and increased compliance of fascia cause hypermobility that especially occurs in various inherited connective tissue disorders such as Ehlers–Danlos Syndrome (EDS), Marfan Syndrome, Cutis Laxa, and Osteogenesis Imperfecta (Schleip et al., 2012). An excessive range of joint movement characterizes them. In contrast, there are stiff and limited range of motion in patients with sclerodermia, spastic paresis, major organ fibrosis, duchenne dystrophy, frozen shoulder, hypertrophic scars etc. (Klingler et al., 2014).

The plantar fasciitis

The plantar fascia includes three bands in different density and originates from the medial tubercle of the calcaneus into the base of each proximal phalanx. It gets tense during the terminal stance to toe-off phases of gait (Gill, 1997). The collagen fibers of plantar fascia are mainly longitudinal but some collagen fibers lie in vertical, transverse, and oblique directions. All collagen fibers is nearly formed of type I. Therefore, the plantar fascia is not an elastic tissue (Stecco et al., 2013). During the gait, it supports the medial longitudinal arch as a rigid lever for forward propulsion (Flanigan et al., 2007). Other important roles of the plantar fascia are to carry proprioceptive sense and to maintain peripheral motor coordination (Stecco et al., 2013).

Calcaneal part of the plantar fascia is commonly degenerated by microtearing. It seems thicken. Besides, fibrosis of the plantar fascia along with collagen necrosis, chondroid metaplasia, and calcification exist (Schepsis et al., 1991). It is named plantar fasciitis that is more common in women. It has high incidence between 45 and 64 years old (Riddle and Schappert, 2004). Additionally, plantar fasciitis is one of the most common causes of heel pain (Thompson et al., 2014).

The primary complaint is medial plantar heel pain on weight bearing during their first few steps in the morning (Gill, 1997). It is aggravated with palpation of medial plantar heel and there is a pain with passive dorsiflexion (Neufeld and Cerrato, 2008). There is no consensus about management of plantar fasciitis (DiGiovanni et al., 2012). Approximately 85–90% of plantar fasciitis can be successfully treated with noninvasive therapy (Thompson et al., 2014). If there is no relief of the complaint nearly 6–12 months after the conservative therapy, surgical treatment can be offered (Thompson et al., 2014).

Frozen shoulder

Frozen shoulder is a common condition which progresses through freezing, frozen and thawing stages, also often associated with diabetes. In spite of the defined clinical progression stages, the causes of primary frozen shoulder remain largely unknown while numerous conditions can trigger the secondary form.

The fascia could be affected in frozen shoulder and in shoulder joint could be contracture and stiffening. There is a hypomobility condition in frozen shoulder. General joint mobility and tissue elasticity could be influenced by myofibroblast density in muscular fascia (Remvig et al., 2007).

Diabetic foot

Diabetes may lead to many vascular and neurological complications, including ulceration, infection, or destruction of deep tissue in the foot (Fig. 10.3). "Diabetic foot" is seen approximately 15% of patients with diabetics (Boulton et al., 2004). Morphological changes in the plantar fascia and achilles tendon, and limitations in joint mobility have been reported in diabetes. Changes in foot structures share a common etiology related to longstanding hyperglycemia and they may influence foot mechanics during gait and lead to foot ulcers (Schleip et al., 2012).

Thickening of plantar fascia can influence biomechanics and functions of foot in patients with diabetes. Increased dynamic forefoot pressures were found in diabetics with thicker plantar fascia to compare diabetics and healthy subjects with thinner plantar fascia (D'Ambrogi et al., 2003; Giacomozzi et al., 2005). Additionally, a significant correlation was found between fascia thickness and forefoot pressure. This relationship may be explained by the role plantar fascia plays in resisting the flattening of the foot during mid-stance of gait.

Consistent findings are the existence of thicker plantar fascia, thicker and shorter achilles tendon, and limitations in the mobility of the foot and ankle joints, all leading to increased plantar foot pressures in diabetic patients. Lengthening of the achilles tendon, mobilization of the foot and ankle joints are commonly used in rehabilitation program for patients with diabetes (Schleip et al., 2012).

Trigger points

Trigger points generally cause pain in the musculoskeletal system (Treaster et al., 2006). The trigger point is a point that is known well by the patient and the symptoms of the patient occur. It is called a myofascial trigger point when the trigger point is on the muscle. If the trigger point is in a tendon, a ligament, the periosteum, it is called a tendinous, ligamentary, or periosteal trigger point, respectively. Trigger point can be silent or active. Active trigger point defines with a localized or referred pain during rest, stress or movement. Silent trigger point is not spontaneously painful at rest or during exercise and does not display clinical symptoms (Travell and Simons, 1999).

FIGURE 10.3 The plantar aponeurosis shown as a low signal intensity structure on this sagittal plane magnetic resonance image of the foot of a neuropathic diabetic patient (Schleip et al., 2012).

Muscle trigger points are characterized by the presence of pain (local or referred), motor function disturbance (reflex muscle weakness without atrophy), autonomic and trophic changes (Travell and Simons, 1999). There can be taut bands between trigger point and connective tissue. These taut bands can cause decreased muscular coordination, reduced mobility, reduced perfusion, irritation of deep sensitivity, altered proprioception and nociception (Schleip et al., 2012), and restricted movement (Lewit, 2007).

Fascia wraps around all organs and body, and connects everything with everything else. Epimysium and thin intramuscular connective tissue structures (endomysium) belong to fascia and fascia is a part of the muscle. Therefore the fascia and the muscle induce each other (Schleip et al., 2012). In case of disrupted function of fascia such as muscle trigger points muscle activation can be negatively affected (Lucas et al., 2004). Changes in muscular connective tissue cause pathological crosslinks that affect intramuscular coordination, metabolic supply, movement and posture. These factors activate trigger points over time. Fascia which has mechanoreceptors works such as receptor organ (Bordoni and Whitte, 2018). These sensory input regulates perfusion and metabolism of the muscles. Perfusion and metabolism of the muscles can also be affected by dysfunction of the fascia. As a result, capacity of regeneration may reduce (Schleip et al., 2012). So it can lead to chronic muscular problems if the trigger points cannot be cured.

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Part 3

Upper extremity

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Chapter 11

Kinesiology of the shoulder complex

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Introduction

The shoulder is an extremely complicated region of the body. The primary function of the shoulder girdle is to position the upper extremity in space for the placement of the hand and to allow the hand to perform its functions such as manipulation of the objects. The shoulder consists of the humerus, scapula, clavicle, ribs and; glenohumeral, acromioclavicular, sternoclavicular, scapulothoracic, upper thoracic, costal, and sternomanubrial joints; and thirty muscles. Movement of the shoulder girdle depends on functional interrelations between these structures. Integrated function of the rotator cuff muscles, scapula stabilizing muscles, joint capsule, ligaments, intra-articular pressure, glenoid concavity, scapular inclination, and labrum provide not only movement but also stabilization of the shoulder. Nevertheless, high degree of mobility in shoulder joint bring along stability issues. Only sternoclavicular joint connects the components of shoulder joint to the axial skeleton. This puts greater demands on the muscles for securing the shoulder girdle on thorax during static and dynamic conditions. The shoulder joint is involved in a variety of overhead activities relative to sport, work, and activities of daily living. These activities make it susceptible to repetitive and overuse injuries. Pain, dysfunction and instability of the shoulder are frequent complaints of the patients who apply to the hospitals. Understanding unique anatomical and kinesiologic features of the shoulder, normal function and dysfunction of the shoulder complex and coordination between the components of the shoulder complex must be taken into consideration in terms of prevention and treatment of shoulder injuries.

Bones of the shoulder complex

The scapula, the clavicle, and the humerus serve as attachments for shoulder joint muscles. The scapula and the clavicle move as a unit. The clavicle articulates with the sternum via sternoclavicular joint allowing considerable mobility in the upper extremity.

Clavicle

Functions of the clavicle, the only bony attachment of shoulder complex to the axial skeleton, are holding the upper extremity suspended on the axioskeleton, protecting nerves and blood vessels, increasing mobility of the shoulder, providing attachment site for muscles and helping transmit muscle force to the scapula (Moseley, 1968).

The clavicle is a crank-shaped bone that lies almost transversely (Fig. 11.1A). The shaft of the clavicle is curved with its anterior surface. It is convex medially and concave laterally. Medial two thirds of the shaft convex anteriorly, lateral one third convex posteriorly. With the arm hanging by the body, the long axis of the clavicle is oriented 20° posterior to the frontal plane and above the horizontal plane (Fig. 11.1B).

The pectoralis major muscle attaches medially and the deltoid muscle laterally to the anterior surface of the clavicle. The upper trapezius muscle attaches to the posterior surface while subclavius muscle and costoclavicular ligament attaches inferomedially and coracoclavicular ligament inferolaterally.

Rounded medial (sternal) end of the clavicle articulates with the sternum and the lateral end with the acromion of the scapula. The conoid tubercle and trapezoid line are markings on the inferior surface of the lateral end of the clavicle. Costal facet of the clavicle articulates with the first costal cartilage.

Scapula

The scapula is a triangular (inferior, superior and lateral), generally flat (could also be rounded or hooked) shaped

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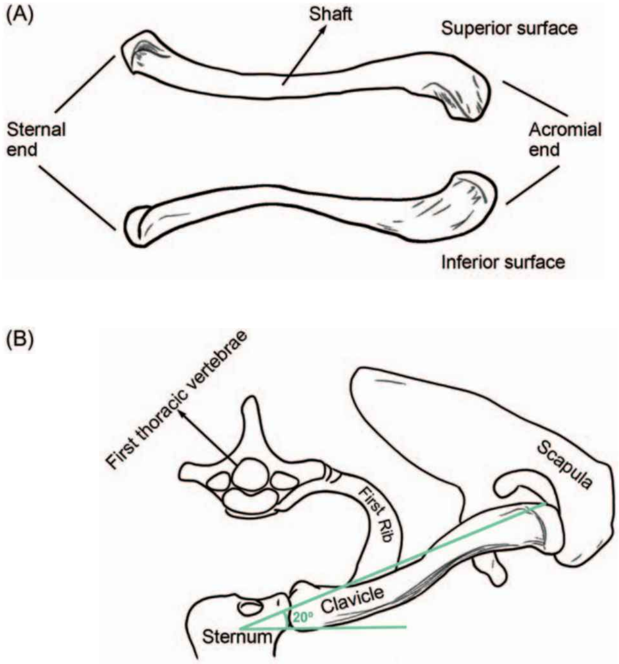

FIGURE 11.1 (A) The clavicle, (B) orientation of the clavicle.

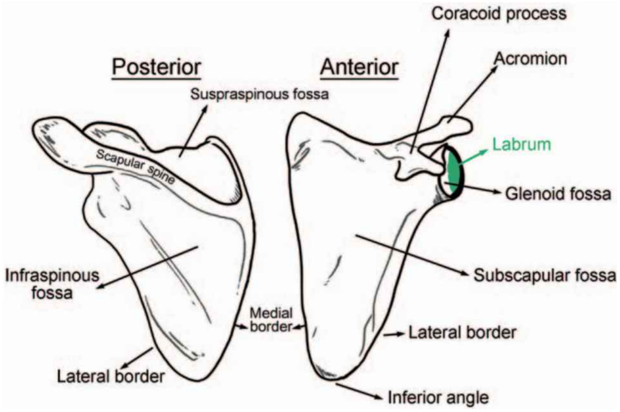

FIGURE 11.2 The scapula.

bone (Bigliani et al., 1996), which also has three borders: medial, lateral, and superior (Fig. 11.2).

Providing site for attachment for 15 muscles (Lucas, 1973), unique function of the scapula allows upper extremity to move freely in reaching and grasping activities.

Subscapularis muscle attaches to smooth anterior surface of the scapula while serratus anterior muscle rises from its medial border. The prominent spine of the scapula divides dorsal surface into two regions: supraspinous fossa and infraspinous fossa. Root of the spine is at the medial end of the spine, flat acromion process that extends anterior-laterally forming a roof over the humeral head is at its lateral end. The clavicular facet of the acromion is covered by fibrocartilage and is at the one side of the acromioclavicular joint.

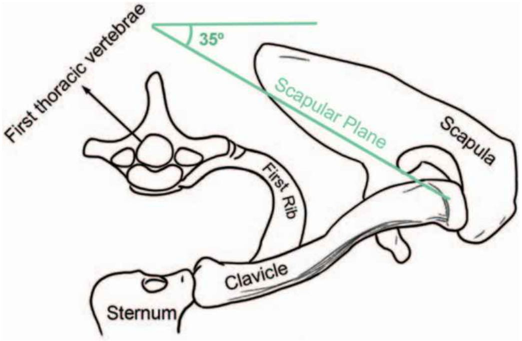

FIGURE 11.3 Scapular plane.

Concave gleniod fossa of the scapula articulates with the humeral head (glenohumeral joint) while it is tilted 5° upwardly relative to the medial border of the scapula. Fibrocartilaginous labrum surrounding the fossa increases its depth. The scapula is inwardly rotated about a vertical axis in a transverse plane. The scapula is positioned against the posterior and lateral surface of the thorax at rest and scapular plane is oriented approximately 30°–45° anteriorly to the frontal plane (Kapandji, 1982; Saha, 1983) (Fig. 11.3).

In the upright posture, scapula is positioned from the first to the eighth ribs and from the spinous processes of about T2 or T3 to T7 vertebrae. The medial aspect of the spine of the scapula is in line with the spinous process of T2 or T3. inferior angle of the scapula is in line with the spinous process of T7. During arm elevation scapula and humerus follow scapular plane and the scapula moves on the superior part of the thorax. Prominent beak shaped coracoid process is projecting from the anterior surface of the superior border of the scapula and it provides attachment sites for muscles and ligaments. Supraglenoid and infraglenoid tubercles of the glenoid fossa are the attachment sites of the long head of the biceps and triceps brachii muscles.

A frontal plane rotation about an axis perpendicular to the plane of the scapula directed anteriorly that tilts the glenoid fossa inferiorly, moving the inferior angle of the scapula medially, is described as downward rotation of the scapula, whereas a rotation that tilts the glenoid fossa upward, moving the inferior angle laterally is upward rotation. The static position of the scapula could be one of those rotations (Freedman and Munro, 1966; Poppen and Walker, 1976; Lukasiewicz et al., 1999). The scapula has anterior/posterior tilting about a laterally directed axis [(approximately 10° anterior tilt in sagittal plane in quite standing (Culham and Peat, 1993)] and internal/external rotation about a superiorly directed axis (Ludewig et al., 2009).

Proper positioning and movement of the scapula on the thorax is crucial for effective shoulder motion (Kibler et al., 2013; Kibler and Sciascia, 2013; Cools et al., 2014). Decreased upward rotation and posterior tilting and increased internal rotation have been found in people with shoulder impingement (Lukasiewicz et al., 1999; Borstad and Ludewig, 2005; Forthomme et al., 2008; Ludewig and Reynolds, 2009). Furthermore, alterations in scapular normal position or any abnormal motion pattern of the scapula during active motions have been termed "scapular dyskinesis" (Kibler et al., 2013; Kibler and Sciascia, 2013).

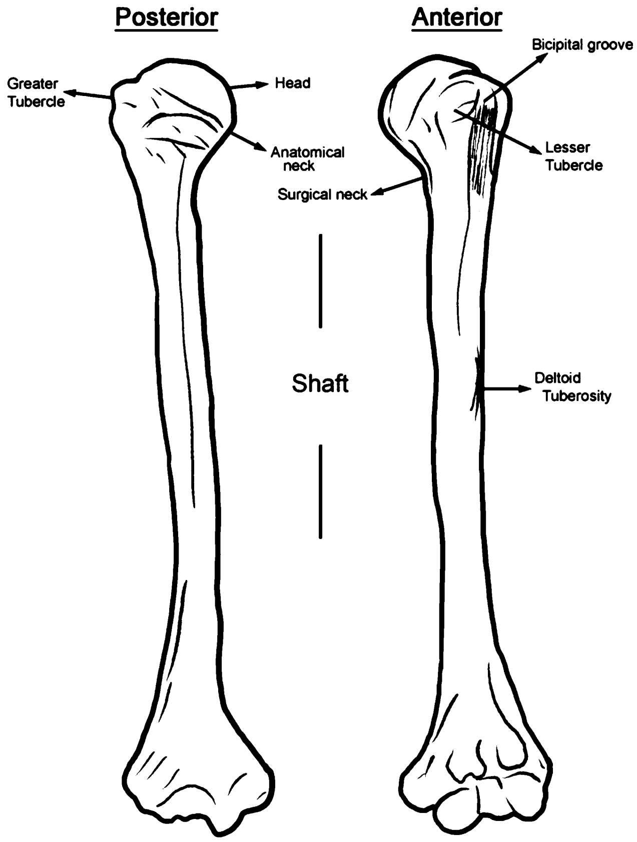

FIGURE 11.4 The humerus.

Proximal-mid humerus

Humerus is composed of head, anatomic neck, surgical neck, shaft (Fig. 11.4). The humeral head is the convex component of the glenuhumeral joint.

There is a 135° angle of inclination between the humeral head and shaft in the frontal plane. Humeral head is retroverted 30° relative to the distal humerus in order to stay in scapular plane (Kronberg et al., 1990a; Edelson, 2000; Friedenberg et al., 2002) (Fig. 11.5).

Prominent and rounded greater tubercle is on the lateral aspect of the proximal humerus and its upper, middle, and lower facets provides attachment for supraspinatus, infraspinatus, and teres minor muscles whereas sharper lesser tubercle on the anterior aspect provides attachment for the subscapularis muscle. Bicipital groove between these tubercles contains the tendon of the long head of the biceps brachii muscle and latissimus dorsi muscle and sharp crests on the anterior sides of the tubercles provides attachments for pectoralis major, and teres major muscles. Deltoid tuberosity, which is located distally and anterior-laterally to the lower end of the bicipital groove provides

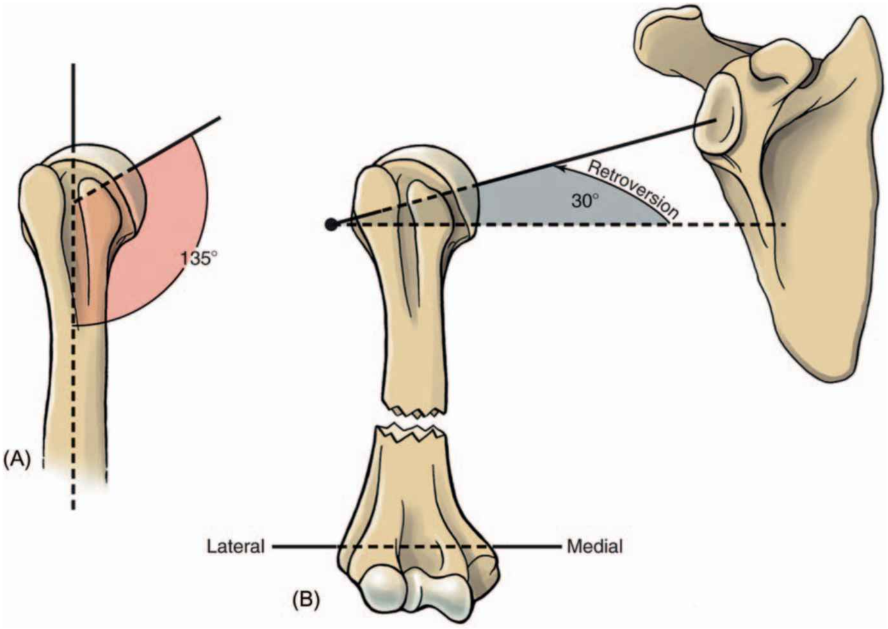

FIGURE 11.5 (A) Humeral head inclination, and (B) retroversion (relative to the distal humerus).

attachment of deltoid muscle. Radial groove is located at the posterior aspect of the proximal humerus separating lateral and medial head of the triceps brachii muscle. The radial nerve and profunda brachii vessels travel in the radial groove.

Sternum

The sternum is composed of the manibrium sterni, body, and the xiphoid process. The manibrium articulates with the clavicle via clavicular facets, and with the first two ribs via costal facets. Prominent jugular notch is located at the superior aspect of the manubrium.

Joints of shoulder complex

Movement of the shoulder complex mainly involves interdependent motions at the sternoclavicular, glenohumeral, acromioclavicular and scapulothoracic joints. Movement of upper thoracic, costal, and sternomanubrial joints are also relevant to shoulder function.

Ludwig et al., reported the average joint positions in quite standing (Table 11.1) (Ludewig et al., 2009).

During humeral elevation general shoulder motion patterns are elevation, retraction, and posterior rotation of the clavicle; internal rotation, upward rotation, and posterior tilting of the scapula relative to the clavicle; and glenohumeral elevation and external rotation. Ludewig et al., found that clavicular posterior rotation predominated at the sternoclavicular joint (average, 31°) whereas scapular posterior tilting predominated at the acromioclavicular joint (average, 19°). The average overall scapulohumeral rhythm was found as 2.1:1 for abduction, 2.4:1 for flexion, and 2.2:1 for scapular plane abduction in their study (Ludewig et al., 2009).

TABLE 11.1 Angular joint positions during quite standing with the arm at the side[a].

Joint	Position (°)[b]
Sternoclavicular joint	
Retraction	19
Elevation	6
Posterior rotation	0.1
Scapulothoracic joint	
Internal rotation	41
Upward rotation	5
Anterior tilting	13
Acromioclavicular joint	
Internal rotation	60
Upward rotation	2
Anterior tilting	8
Glenohumeral joint	
Elevation	1
Plane of elevation	3
External rotation	14

[a] *Actual values of position from Ludwig et al.'s study (Ludewig et al., 2009) are rounded off to the nearest integer.*

[b] *All angles are relative to the cardinal planes of the trunk with the exception of acromioclavicular (scapula relative to the clavicle) and glenohumeral (humerus relative to the scapula).*

Sternoclavicular joint

The sternoclavicular joint is a synovial, triaxial (anterior—posterior, superior—inferior, and longitudinal (Fig. 11.6) joint usually described as ball-and-socket or saddle joint (Gray et al., 1995) with 3° of freedom.

It is the only joint connects the components of shoulder joint to the axial skeleton. The sternoclavicular joint includes the medial end of the clavicle, the clavicular facet of the sternum and the superior border of the first costal cartilage (Fig. 11.7).

The "S" shaped architectural design of the clavicle is likened to a crank. This distinctive shape enables the muscles to increase the power and velocity of upper extremity movements such as throwing, whereas making the clavicle weaken for compressive loading. The junction between the medial convexity and its lateral concavity is a weak point, which is a common site for fractures.

Medial end of the clavicle convex along its longitudinal diameter and concave along its transverse diameter, whereas clavicular facet concave along its longitudinal diameter and convex along its transverse diameter. Articular disc of the sternoclavicular joint binds the joint together and improves the congruity of incompatible dimensions of the articular surfaces of the sternum and clavicle. The sternoclavicular joint is divided into two synovial cavities with the inferior and superior attachments of the disc to the first costal cartilage and the articular surface of clavicle, respectively. The costochondrium of the first rib forms the floor of the joint. Joint has a synovial capsule that is weaker inferiorly then it is anteriorly, posteriorly, and superiorly thanks to ligaments that are thickening the capsule at those directions.

Static stabilizers of the sternoclavicular joint are anterior and posterior sternoclavicular ligaments to limit anterior and posterior slide of the joint, and protraction and retraction; interclavicular ligament connecting right and left clavicles to limit superior, inferior and lateral movement of the clavicle; two bundled (anterior and posterior) (Gray et al., 1995) costaoclavicular ligament to limit

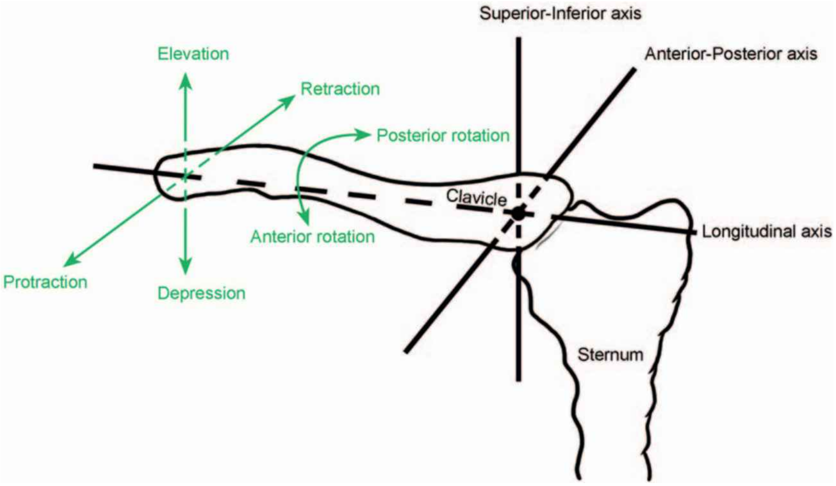

FIGURE 11.6 Axes of motion of the sternoclavicular joint.

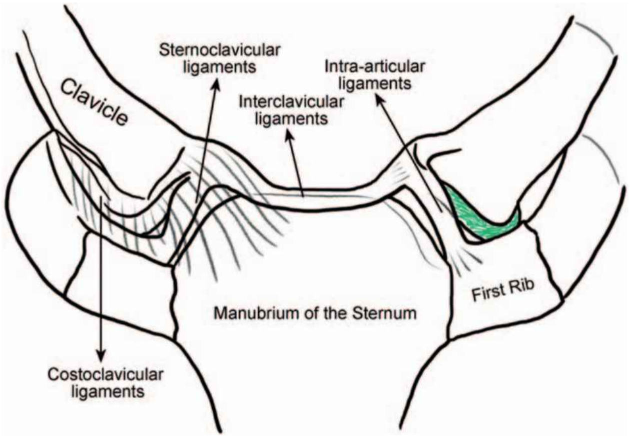
Sternoclavicular ligaments
Intra-articular ligaments
Clavicle
Interclavicular ligaments
Manubrium of the Sternum
First Rib
Costoclavicular ligaments

FIGURE 11.7 The sternoclavicular joint.

clavicular motions except for depression; the articular disc to absorb shocks by increasing the joint contact area and to limit medial movement of the clavicle; and finally the costal cartilage to limit inferior movement of the clavicle. Dynamic stabilizers of the sternoclavicular joint are sternocleidomastoid, sternothyroid, and sternohyoid muscles (Moseley, 1968). Clavicular fractures, which generally are traumatic, are more common than sternoclavicular joint dislocations due to quite stable sternoclavicular joint.

Kinematics

Triaxial clavicular movements are elevation and depression occur about anterior–posterior axis, protraction and retraction occurs about superior–inferior axis, and anterior and posterior rotation occurs about longitudinal axis (Fig. 11.8).

These clavicular movements in the sternoclavicular joint are associated with scapular motions and are essential for normal shoulder function.

Elevation occurs as the convex articular surface of the clavicular head rolls in superior direction and slides in inferior direction whereas depression occurs as the clavicular head rolls in inferior direction and slides in superior direction (Fig. 11.9).

Total elevation and depression of the clavicle was found as 45°–60° and around 10°, respectively (Conway, 1961; Moseley, 1968). The costoclavicular ligament limits elevation whereas the superior capsular ligaments and interclavicular ligament limit depression.

Protraction occurs as the concave articular surface of the clavicle rolls and slides in anterior direction on the convex surface of the sternum whereas **retraction** occurs as the concave articular surface of the clavicle rolls and slides in posterior direction (Fig. 11.10).

Total protraction and retraction was found similar as 15°–30° to 60° (Conway, 1961; Moseley, 1968; Pronk et al., 1993). The costoclavicular ligament, posterior sternoclavicular ligament, interclavicular ligament, and scapular retractor muscles limit protraction whereas the anterior sternoclavicular ligament, interclavicular ligament, and the costoclavicular ligament limit retraction.

Posterior rotation and anterior rotation occur as the head of the clavicle spin about the lateral surface of articular disc. Clavicle rotates posteriorly in shoulder elevation while anterior rotation occurs in shoulder depression. Total anterior and posterior rotation was found as 20°–50° and less than 10°, respectively (Bearn, 1967; Pronk et al., 1993; van der Helm and Pronk, 1995; Inman et al., 1996).

More detail was reported in Ludewig et al.'s study (Ludewig et al., 2009). During arm elevation in all three planes increased clavicular retraction (an average increase of 16°, from an initial position of 23° to an end position of 39°), elevation (an average increase of 6°, from 11° to 17°), and posterior rotation (an average increase of 31°, from 0°) of the clavicle relative to the thorax was found

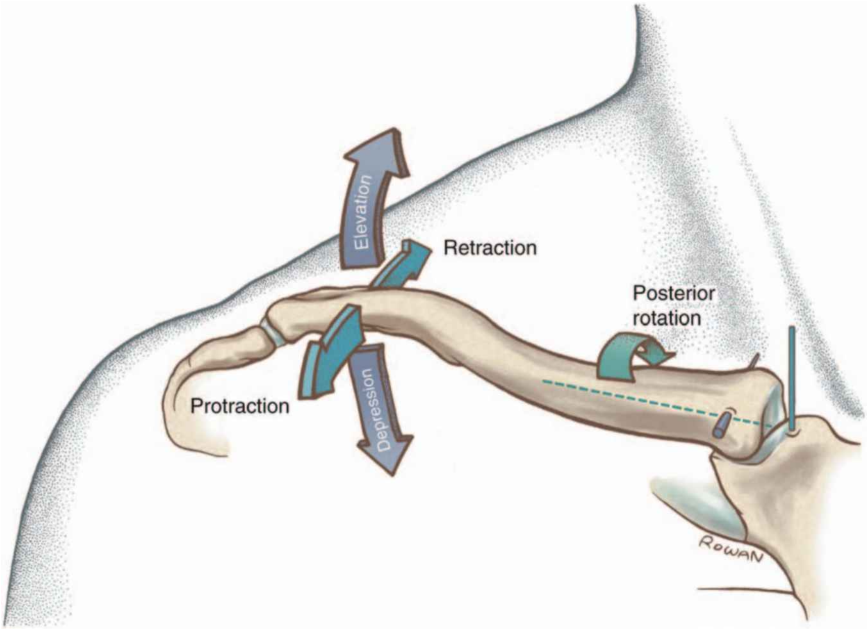

FIGURE 11.8 Osteokinematics of the clavicle.

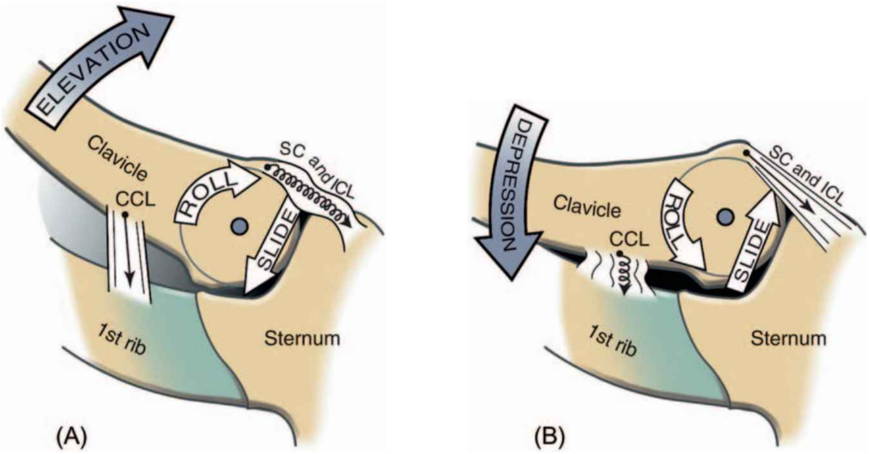

FIGURE 11.9 Arthrokinematics of the clavicle during elevation and depression.

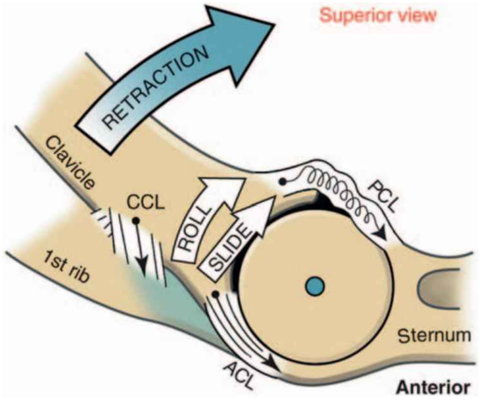

FIGURE 11.10 Arthrokinematics of the clavicle during retraction.

at the sternoclavicular joint. Closed pack position of the sternoclavicular joint is full posterior rotation of the clavicle (Gray et al., 1995). Arm by the side position is the loose pack position of the joint.

Acromioclavicular joint

The acromioclavicular joint is a synovial joint with 3° of freedom that is located between acromion and the lateral end of the clavicula (Fig. 11.11).

The joint is generally described as a gliding joint with flat joint surfaces (Gray et al., 1995) covered by fibrocartilage. Articular facets of clavicle and acromion are variable in size and shape. Most acromioclavicular joints have

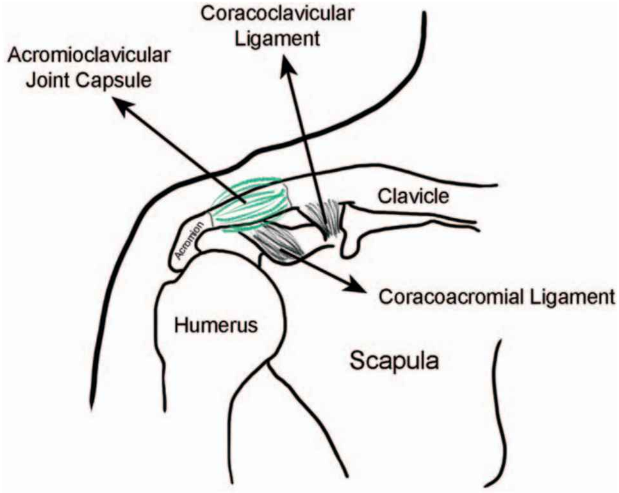

FIGURE 11.11 The Acromioclavicular joint.

a complete or incomplete intraarticular disc (meniscus) (Lee and An, 2002). A capsule supports the joint, which is more lax than the sternoclavicular joint contributing to the increased risk of dislocations especially during contact sports (Moseley, 1968), although superior and inferior acromioclavicular ligaments primarily reinforces it (Fig. 11.11). The acromioclavicular ligaments limit posterior slide of the acromioclavicular joint and excessive anterior displacement of the clavicle on the scapula (Lee et al., 1997). The deltoid and trapezius muscles reinforce superior capsular ligaments. Extracapsular coracoclavicular ligament, consists of trapezoid and conoid ligaments, provide additional stability limiting large excursions and medial movements (Fukuda et al., 1986, Dillman et al., 1993; Bigliani et al., 1996; Lee et al., 1997). Scapular motion is translated to the clavicle by the help of these two ligaments (Dempster, 1965). There is also coracoacromial ligament protecting underlying bursa and supraspinatus tendon as well as limiting superior slide of the humerus in case the glenohumeral joint is too unstable (Lucas, 1973).

Kinematics

The major movement of the acromioclavicular joint is the rotation of the clavicle. Although gliding joints allow only translational movements, rotational movement around three axes described at the acromioclavicular joint (Culham and Peat, 1993; Pronk et al., 1993; Gray, Williams et al., 1995): Longitudinal axial rotation, vertical axis for protraction and retraction, and horizontal axis for elevation and depression.

Angular excursions are less than 10°–20° about each axis (Pronk et al., 1993; Inman et al., 1996). Acromioclavicular joint motion is defined as the scapular motion relative to the clavicle. Upward and downward rotation of the scapula about an axis perpendicular to the plane of the scapula directed anteriorly (Fig. 11.12) occurs primarily in the acromioclavicular joint and secondary internal and external rotations between 10° and 30° about a superiorly directed axis (Fig. 11.12) provides fine-tuning for the final scapular position against the thorax (Conway, 1961; van der Helm and Pronk, 1995, Branch et al., 1996). Up to 30° upward rotation reported as varied angles between 11° and 30° occurs during overhead arm elevation (Moseley, 1968; van der Helm and Pronk, 1995; Inman et al., 1996; McClure et al., 2001; Ludewig et al., 2009). The third scapular rotation relative to the clavicle or thorax is anterior/posterior tilting about a laterally directed axis (Fig. 11.12) (Sahara et al., 2007; Ludewig et al., 2009) (Fig. 11.13).

During arm elevation in all three planes increased scapular internal rotation (an average increase of 8°, from an initial position of 57° to an end position of 65°), upward rotation (an average increase of 11°, from 5° to 16°), and posterior tilting (an average increase of 19°, from −4° to 15°) relative to the clavicle was found at the acromioclavicular joint (Ludewig et al., 2009). Closed pack position of the acromioclavicular joint is full scapular upward rotation in full elevation (Gray et al., 1995). Arm by the side position is the loose pack position of the joint.

Scapulothoracic joint

The scapulothoracic joint is not a true synovial joint. Rather, it is a contact point between anterior surface of the scapula and posterior wall of the thorax (Williams et al., 1999). This physiologic joint has no ligamentous support but rather it is dynamically supported by the muscles. Movement of this joint movement depends on acromioclavicular and sternoclavicular joints that allow the scapular motions (Ludewig et al., 2004b; Teece et al., 2008; Matsuki et al., 2012). The primary role of this joint is to improve the glenohumeral joint motions. Therefore, the large movement (a composite movement of the acromioclavicular and sternoclavicular joints) available in the scapulothoracic joint provides the wide range of shoulder motion.

Kinematics

Motions available in the scapulothoracic joint are elevation and depression, abduction and adduction, downward and upward rotation, internal and external rotation, and anterior and posterior scapular tilt.

Scapular elevation describes the superior movement of the scapula on the thorax. Clavicular elevation about the sternoclavicular joint and scapular downward rotation about the acromioclavicular joint provides scapular elevation. Scapular depression is the reverse movement (Fig. 11.14).

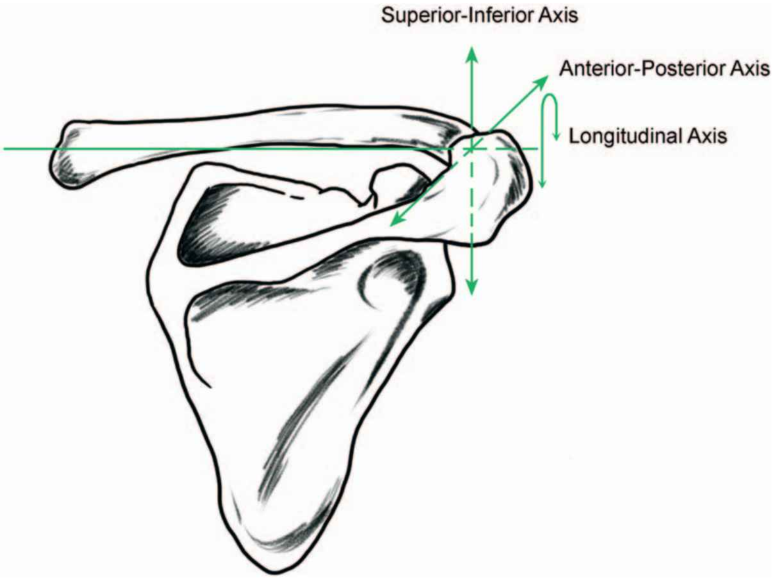

FIGURE 11.12 Axes of motion of the acromioclavicular joint.

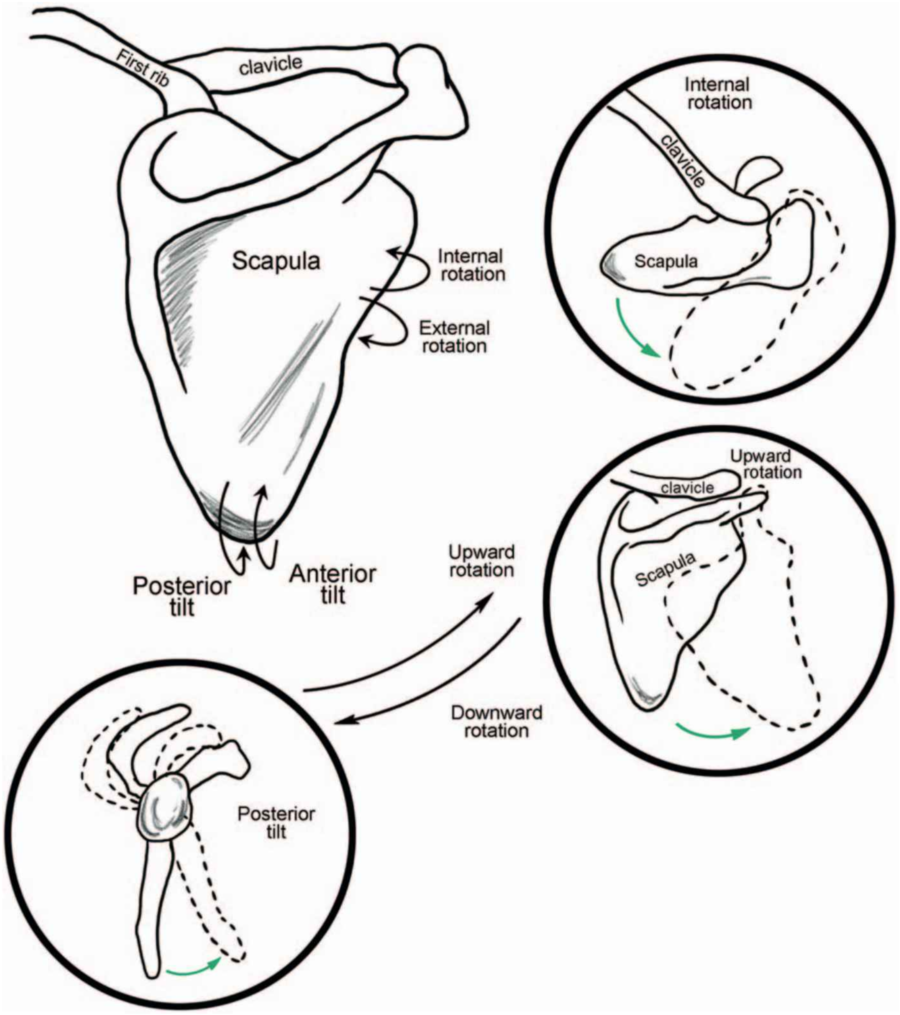

FIGURE 11.13 Osteokinematics of the acromioclavicular joint.

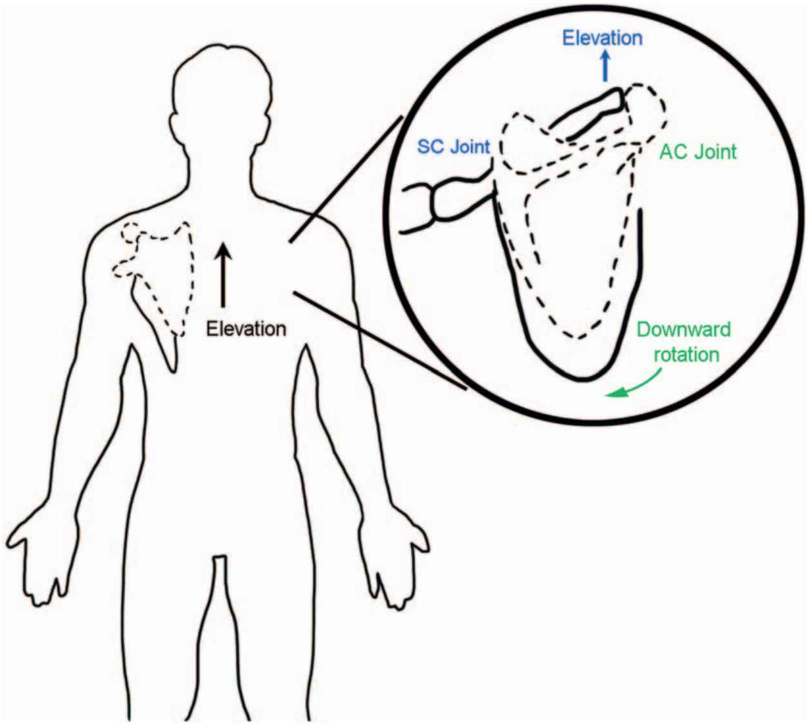

FIGURE 11.14 Scapulothoracic elevation.

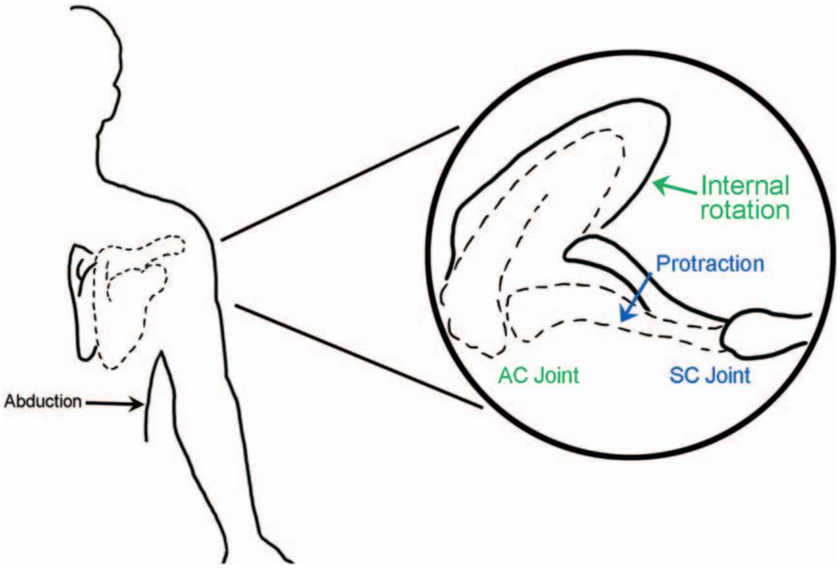

FIGURE 11.15 Scapulothoracic abduction.

Scapulothoracic elevation is a result of sternoclavicular elevation (Teece et al., 2008; Ludewig et al., 2009). 55° scapular elevation and depression corresponding to 2–10 cm excursions occur at the joint (Kapandji, 1982; Kelley and Clark, 1995).

Abduction (protraction) describes the lateral movement of the scapula on the thorax moving away from the spinal column. Clavicular protraction about the sternoclavicular joint and horizontal plane adjustments about the acromioclavicular joint provides scapular abduction (Fig. 11.15).

Adduction (retraction) is the reverse movement that occurs during activities like pulling an object towards the body. Abduction and adduction is a result of sternoclavicular protraction and retraction (Teece et al., 2008; Ludewig et al., 2009). 25° scapular abduction and adduction occurs at the joint.

Upward rotation describes the rotation about an anterior posterior axis resulting in upward turn of the glenoid fossa as the inferior angle moves away from the spinal column. Clavicular elevation about the sternoclavicular joint and scapular upward rotation about the acromioclavicular joint provides scapular abduction (Fig. 11.16).

Downward rotation is the reverse movement that occurs during returning to the quite standing position. 60° scapular upward and downward rotations occur at the joint (Poppen and Walker, 1976; Inman et al., 1996; McClure et al., 2001).

Internal rotation describes the rotation about a vertical axis resulting in turn of the axillary border of the scapula more anteriorly. External rotation is the reverse movement. Scapular internal rotation occurs with scapular abduction whereas external rotation occurs with scapular adduction. 25° scapular external rotation occurs at the joint (Oatis, 2009).

Anterior tilt of the scapula describes the motion about a medial-lateral axis resulting in movement of the superior portion of the scapula anteriorly while moving the inferior angle of the scapula posteriorly. Posterior tilt is the reverse movement. Scapular anterior tilt occurs with scapular elevation whereas posterior tilt occurs with scapular depression (Fig. 11.17). In quite standing anatomic position, position of the scapula is 10° anterior tilt and 30−40° internal rotation. The scapula posteriorly tilts 20° and rotates internally or externally (Kibler and McMullen, 2003; Oatis, 2009; Kibler et al., 2012; Camargo et al., 2013).

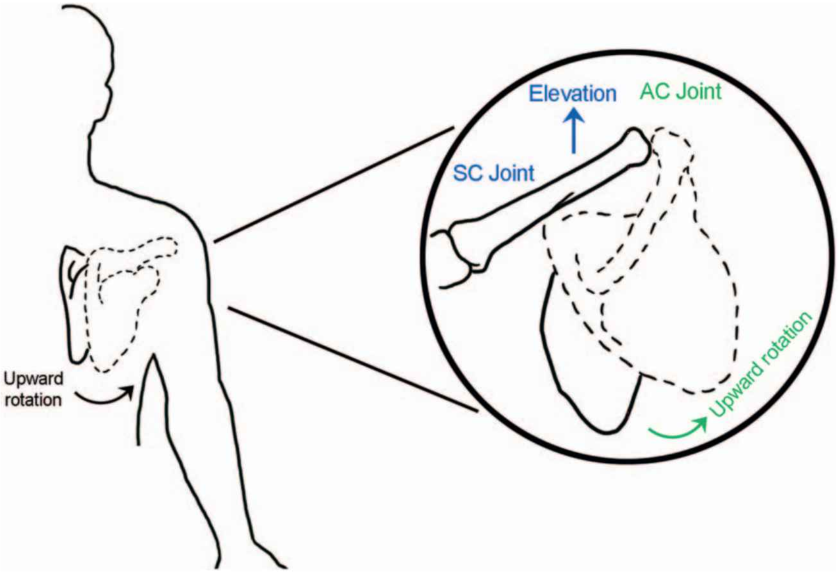

FIGURE 11.16 Scapulothoracic upward rotation.

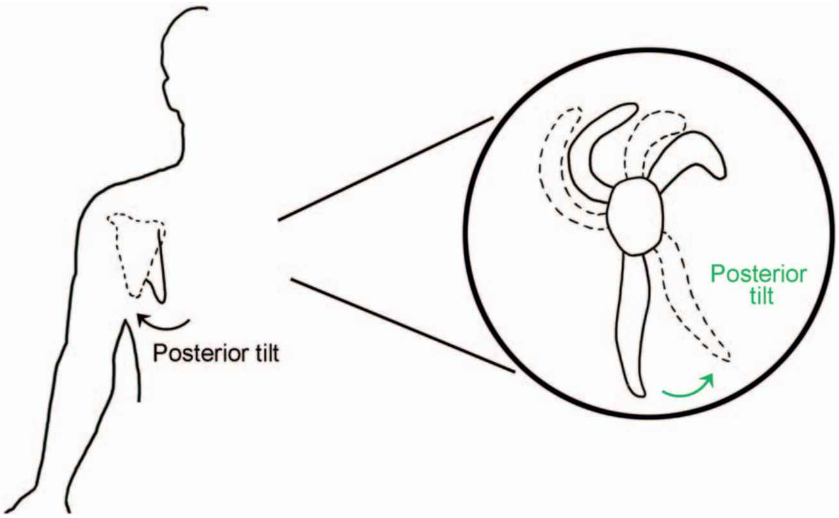

FIGURE 11.17 Scapular motion on the thorax.

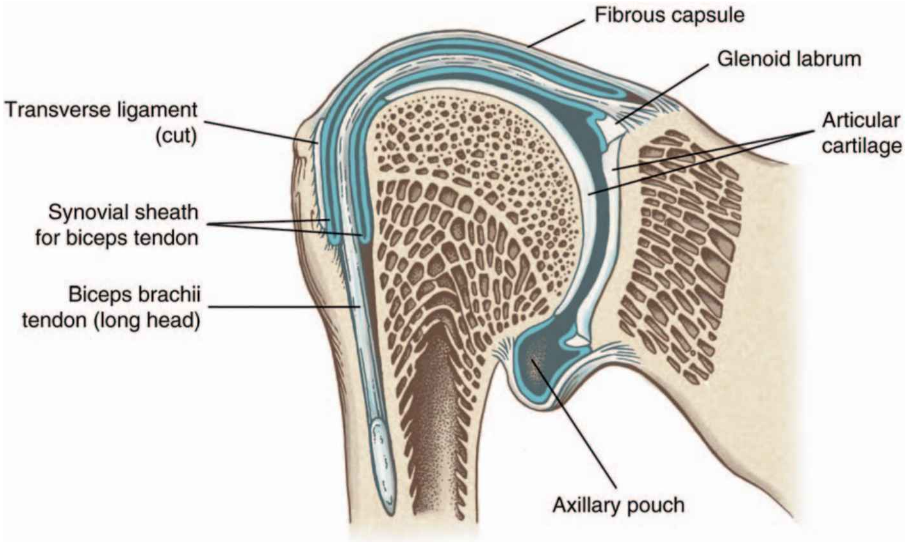
Fibrous capsule
Glenoid labrum
Transverse ligament (cut)
Articular cartilage
Synovial sheath for biceps tendon
Biceps brachii tendon (long head)
Axillary pouch

FIGURE 11.18 The glenohumeral joint.

Glenohumeral joint

The glenohumeral joint is a synovial, simple ball-and-socket joint with 3° of freedom (Curl and Warren, 1996). The joint is composed of convex humeral head and concave glenoid fossa that are both covered with hyaline cartilage (Fig. 11.18).

The glenohumeral joint is the most mobile joint. During quite standing in anatomic position, articular surface of the glenoid fossa is anterior-laterally directed in the scapular plane and in slight upward rotation, and articular surface of the humerus is medially, superiorly and posteriorly directed with regard to the shaft of the humerus and the humeral condyles. Thus, the humeral head is positioned in line with the glenoid fossa within the direction of scapular plane (Churchill et al., 2001). The angle of inclination of the humerus is between 130° and 150°, and the angle of torsion is 30° posteriorly.

Spherical cartilaginous articular surfaces of the humeral head and the glenoid fossa fit well together since they have similar radius of curvature (Iannotti et al., 1992; Soslowsky et al., 1992; Van der Helm et al., 1992). Thanks to this congruence, loads on the joint can spread to a wider surface area while reducing the compressive forces applied to the articular surface. In the other hand, the actual areas of these individual articular surfaces are different even they have similar radius of curvature. The surface area of the glenoid fossa is not even half the size of the humeral head (longitudinal diameter and transverse diameter of the humeral head is approximately 1.9 times and 2.3 times larger than the diameter of the glenoid fossa, respectively) (Kent, 1971; Jobe and Iannotti, 1995; Churchill et al., 2001) (Fig. 11.19).

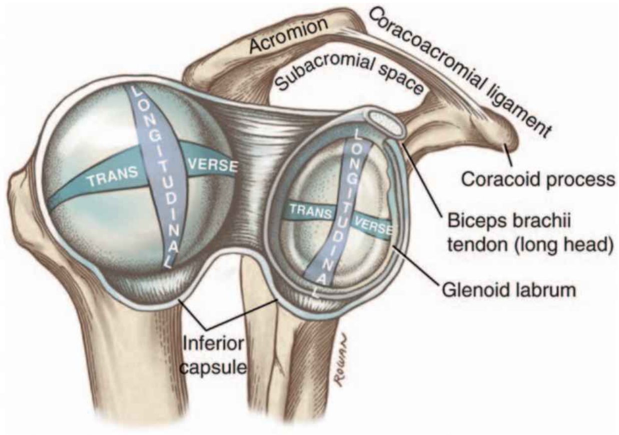

FIGURE 11.19 Articular surfaces of the glenohumeral joint.

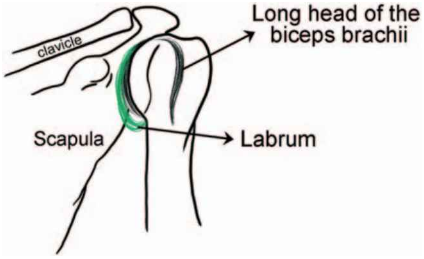

FIGURE 11.20 The Glenoid labrum.

However, the labrum, a fibrocartilage structure that runs around the periphery of the cavity, doubles the depth of the glenoid cavity and improves stability (Cooper et al., 1992) (Fig. 11.20).

With the glenoid and the depth of the socket reaches 9 mm in the superior-inferior direction and 5 mm in the anterior-posterior direction (Bowen and Warren, 1991). Nevertheless, as there is no bony limitation to the excursion, the glenohumeral joint has a large degree of mobility but compromising joint stability at the same time (Lucas, 1973; Veeger and van der Helm, 2007). In dislocations for the first time usually the labrum is ripped off making glenoid cavity shallower (Novotny et al., 1998). This predisposes the shoulder joint to repeated dislocations.

A fibrous joint capsule that attaches along the periphery of the glenoid fossa and labrum to the anatomic neck of the humerus surrounds the glenohumeral joint. Inferior portion of the capsule is loose and forms folds, which are unfolded during arm elevation. A synovial membrane lines the inner wall of the capsule and extends to the tendon of the long head of the biceps brachii muscle. The volume of space within the capsule is about twice the size of the humeral head, which is also one of the contributing factors for great mobility in the glenohumeral joint. Capsule itself is lax. However, the glenohumeral ligaments reinforce the capsule and it is supported by the rotator cuff muscles; supraspinatus, infraspinatus, ters minor, and subscapularis to increase stability. Actual compressive load that is increasing stability is provided by dynamic contraction of these muscles. Central position of the humeral head is highly important to maintain normal compressive forces of the rotator cuff muscles to enhance dynamic stability. In contrast, rotator cuff muscle weakness decreases stability and promotes poor joint athrokinematics. Furthermore, the line of pull of the deltoid muscle is in superior direction and parallel to the glenoid surface creating a maximum shear force at about 60° of glenohumeral abduction. This action of the deltoid may result in a more off-center joint reaction force that could cause mechanical dysfunctions of the shoulder complex such as impingement syndrome and rotator cuff tears (Donatelli, 2012). The long and short heads of the biceps brachii muscle (Itoi et al., 1993) and coracohumeral ligament, the strongest supporting ligament of the glenohumeral joint, retrotilt of the glenoid, and negative intra-articular joint pressure also have role in the stability of the joint (Inokuchi et al., 1997; Itoi et al., 1998). Rotator cuff muscles make a major contribution to the stability of the glenohumeral joint especially during active motion. The posterior capsule, reinforced by the inferior glenohumeral ligament, resists excessive posterior slide of the humeral head and internal rotation of the glenohumeral joint. Despite the well support in anterior, superior, and posterior directions inferior portion of capsule has no additional support at all. Inferior support of the glenohumeral joint is controversial. The coracohumeral ligament and the superior glenohumeral ligament were reported as the limiting structures for inferior slide of the humeral head in some studies (Harryman et al., 1992; Curl and Warren, 1996; Itoi et al., 1998) whereas another study reported that the superior glenohumeral ligament could give very little support for inferior slide (Soslowsky et al., 1997). The reason for this discrepancy among the studies might be associated to the differences in the position of the glenohumeral joint and the magnitude of the humeral displacements (Oatis, 2009).

Adhesive capsulitis

Adhesive capsulitis also known as frozen shoulder is a self-limiting condition characterized by the forming of adhesions in the glenohumeral joint capsule with an insidious onset over 35 years of age. Anteriosuperior joint capsule, axillary recess, and the coracohumeral ligament are affected. Excessive thickening in the inferior capsular ligament of the glenohumeral joint is associated with this condition (Grubbs, 1993; Dias et al., 2005; Kelley et al., 2009). As a result of capsular thickening and restrictions, the capsule is no longer able to unfold to allow full ROM. Even so, the scapula still can achieve its full 60° of upward rotation and the arm can reach 60° of shoulder abduction (assuming neutral glenohumeral positioning) (Levangie and Humprey, 2000). Tight anterior capsule and mild or moderate synovitis but no actual adhesions were determined in these patients. Contracture of the rotator cuff interval is related with the decreased ROM seen in this population (Kelley et al., 2009).

Primary physical findings are pain and restricted active and passive glenohumeral ROM of $\geq$ 25% in at least two directions (Grubbs, 1993; Dias et al., 2005; Kelley et al., 2009). Restrictions are significant in shoulder abduction and external rotation (Dias et al., 2005; Kelley et al., 2009). Capsular pattern of restriction, altered scapulohumeral rhythm, and crepitus is also seen. Secondary impairments are decreased motor control and muscle performance (Grubbs, 1993; Neviaser and Neviaser, 2011).

Exact etiology of this musculoskeletal condition is unknown and it is still a poorly understood condition (Grubbs, 1993). Provoking chronic inflammation in joint capsule or rotator cuff tendons may lead to a primary adhesive capsulitis. Moreover, conditions such as osteoarthritis, rheumatoid arthritis, fractures, immobilization, diabetes mellitus and other metabolic conditions may lead to secondary adhesive capsulitis (Grubbs, 1993; Neviaser and Neviaser, 2011).

Coracohumeral ligament, strongest ligament of the glenohumeral joint, gives additional support to the glenohumeral joint. Proximal attachment of the coracohumeral ligament is at the lateral side of the coracoid process. Distal attachment of the ligament is at the anterior side of the greater tubercle of the humerus. The ligament blends with the capsule and insert into the borders of the supraspinatus tendon and subscapularis (Harryman et al., 1992). The coracohumeral ligament strengthens the rotator cuff interval, capsular space between the tendons of the supraspinatus and subscapularis muscles (Burkart and Debski, 2002). The ligament is taut in extremes of external rotation, flexion, and external rotation; inferior translation of the humeral head from 0° to 50° of abduction (Kapandji, 1982; Thomas and Friedman, 1989; Burkart and Debski, 2002). It also provides protection against excessive posterior slides of the humerus (Blasier et al., 1997).

Three glenohumeral (capsular) ligaments thicken and strengthen the joint capsule. The superior glenohumeral ligament blends with coracohumeral ligament. Proximal attachment of the superior glenohumeral ligament is at the superior labrum and base of the coracoid process covering the anterior attachment of the long head of the biceps brachii muscle (Burkart and Debski, 2002). Distal attachment of the ligament is at the superior aspect of the humeral neck above the lesser tubercle. The ligament is taut in full adduction and during inferior and posterior humeral translations (Warner et al., 1992). The superior glenohumeral ligament is the primary restraint to inferior translation in adduction and main static stabilizer for shoulder abduction at 45° and 90° (Warner et al., 1992). The superior glenohumeral ligament, the coracohumeral ligament and the tendon of the long head of the biceps brachii muscle lies in rotator cuff interval.

The middle glenohumeral ligament blends with subscapularis tendon and anterior capsule. Proximal attachment of the middle glenohumeral ligament is at the superior and middle aspects of the anterior rim of the glenoid. Distal attachment of the ligament is along the anterior aspect of the anatomic neck of the humerus just above the lesser tuberosity. The ligament is taut in early ranges of abduction, extension and external rtation. Additionally, it provides anterior stability resisting anterior translation of the humerus (O'Brien et al., 1990). At 45° of abduction, middle glenohumeral ligament, subscapularis, and inferior glenohumeral ligament resists external rotation. The most important structure that resists to passive external rotation in adducted shoulder is subscapularis.

The inferior glenohumeral ligament is a thick hammock-like structure that has anterior and posterior bands, and axillary pouch that connecting these bands (Turkel et al., 1981) (Fig. 11.21).

Proximal attachment of the inferior glenohumeral ligament is at anterior-inferior, posterior and middle sides of the glenoid labrum. Distal attachment of the ligament is at anterior-inferior, posterior-inferior and middle sides of the anatomic neck of the humeral head. The inferior glenohumeral ligament is the most important stabilizer against anterior-inferior shoulder dislocation (Burkart and Debski, 2002; Eberly et al., 2002). All fibers of the ligament are taut in 90° abduction, anterior band in abduction and external rotation, and posterior band in abduction and internal rotation. The ligament also restricts external rotation at 90° of abduction.

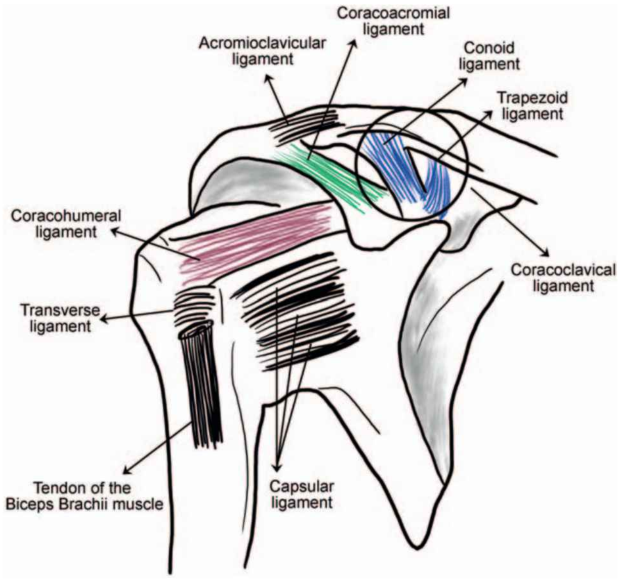

FIGURE 11.21 Ligaments of the glenohumeral joint.

The capsuloligamentous complex reinforces the glenohumeral joint. The glenohumeral ligaments resist anterior displacement of the humeral head on the glenoid fossa in external rotation of the glenohumeral joint (Novotny et al., 1998; Moore et al., 2004; Kuhn et al., 2005) (Fig. 11.20). According to the circle theory, excessive translation of the humeral head in one direction may damage the capsule both on the same and the opposite sides of the joint (Hjelm et al., 1996).

Static stability is the stable state of the humeral head against the glenoid fossa in quite standing position with arms at the side. In this position superior capsular structures with coracohumeral ligament stabilize the glenohumeral joint. Muscle force holds the glenoid fossa in slight upward rotation and passive tension in the taut superior capsular structure and force produced by gravity yields a compression force against the glenoid fossa that locks the joint (Basmajian and Bazant, 1959). This locking system to hold the humeral head in the glenoid fossa is referred as static locking mechanism at the glenohumeral joint (Fig. 11.22).

The supraspinatus muscle and the posterior portion of the deltoid muscle also help the static stability with their lines of pull that is nearly parallel to the lines of pull of aforementioned superior capsular structures. In contrast, poor scapulothoracic posture (Borstad, 2006) or muscular problems associated with insufficient upward rotation reduces the compressive force by increasing the angle between the force vectors of superior capsular structures and gravity. As a consequence of the continuous pull of the gravity in inferior direction glenohumeral joint instability may occur.

Synovial bursa lie between the ligaments and the muscles of the glenohumeral joint in order to modulate frictional forces between muscles, tendons, capsule, ligaments or bones. Subacromial bursa lies within the subacromial space between the supraspinatus muscle and acromion to protect supraspinatus from the acromion. Subdeltoid bursa, as an extension of the subacromial bursa, modulates frictional forces between deltoid muscle, supraspinatus tendon and the humeral head (Fig. 11.23).

The coracoacromial arch formed by the coracoacromial ligament and the acromion is the roof of the glenohumeral joint. Subacromial space between the undersurface of the coracoacromial arch and humeral head is approximately 10–11 mm in healthy adults and similar or slightly less in patients with subacromial impingement syndrome. It contains the supraspinatus muscle and tendon, the subacromial bursa, the long head of the biceps brachii muscle, and the superior portion of the glenohumeral joint capsule. Shoulder elevation narrows the subacromial space to 5–7 mm by moving the greater tubercle closer to the acromion. Changes in the supraspinatus tendon and the direct mechanical compression of the supraspinatus tendon in the subacromial space are two of the many factors that have been proposed as contributors to the development of shoulder impingement syndrome (Neer, 1983; Michener et al., 2003). Decreased subacromial space or greater percentage of subacromial space occupied with the supraspinatus tendon has been shown in shoulders with impingement syndrome (Michener et al., 2015).

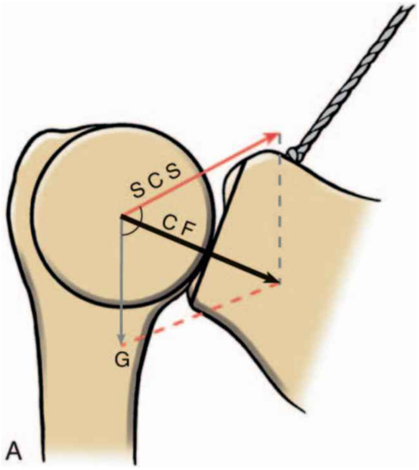

FIGURE 11.22 Locking system at the glenohumeral joint.

Kinematics

The primary motions at the glenohumeral joint are flexion, extension, abduction, adduction, internal rotation and external rotation (Fig. 11.24).

Secondary motions of the joint are horizontal abduction and horizontal adduction. The humerus moves anteriorly and posteriorly at 90° of shoulder abduction during horizontal adduction and horizontal abduction, respectively.

Flexion and extension are defined as the sagittal plane rotation of the humerus about a medial-lateral axis of rotation (Fig. 11.24). During motions in the sagittal plane, significant spinning of the humeral on the glenoid fossa occurs without much roll or slide. This spinning of the humeral head makes capsular structures taut and posterior capsule translates the humerus anteriorly during the end ranges of flexion (Harryman et al., 1990). Shoulder flexion in the sagittal plane occurs with internal rotation (Saha, 1983; Blakely and Palmer, 1984; Palmer and Caslowitz, 1995) especially over 90° of shoulder flexion whereas no or little rotation occurs with shoulder flexion in the scapular plane (Moore et al., 2004). 120° of flexion in a total of 180° shoulder flexion occurs in the glenohumeral joint while scapular upward rotation is needed for the remained 60° to be completed. Most of the range of motion for shoulder extension is achieved by the contribution of the glenohumeral joint and to a lesser degree by the

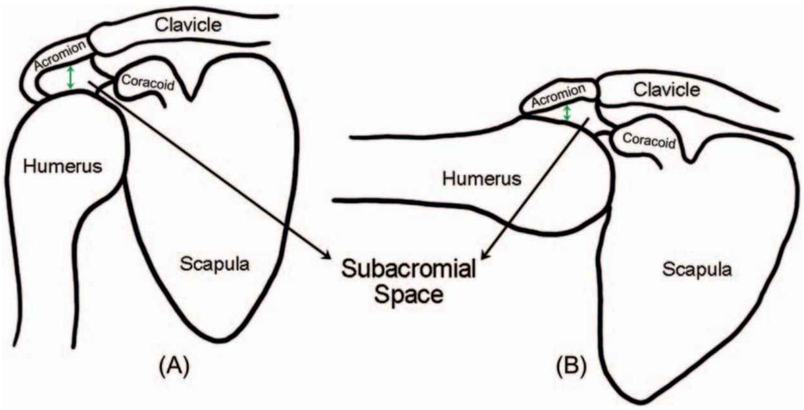

FIGURE 11.23 Subacromial space.

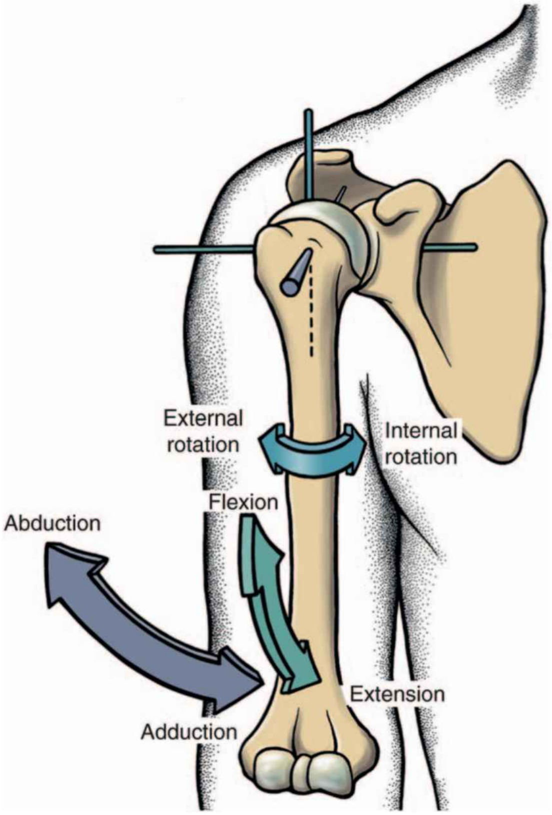

FIGURE 11.24 Osteokinematics of the glenohumeral joint.

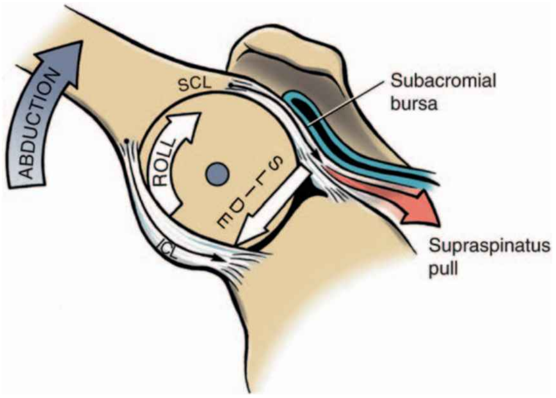

FIGURE 11.25 Arthrokinematics during shoulder abduction.

scapulothoracic joint adduction, downward rotation and anterior tilt (Oatis, 2009). 55°—60° of extension is available to the glenohumeral joint.

Abduction and adduction are defined as the frontal plane rotation of the humerus about an anterior-posterior axis (Fig. 11.24). Convex humeral head rolls superiorly and slides inferiorly during abduction (Fig. 11.25) and the reverse arthrokinematics occur during adduction.

In order to achieve full shoulder abduction sufficient inferior slide is needed. Otherwise superior roll of the humeral head impinge the head against the coracoacromial arch preventing the rest of motion occur. If the humeral head rolls without inferior slide it superiorly translates through the 10—11 mm coracoacromial space after 22° of shoulder abduction impinging supraspinatus muscle and tendon, and the subacromial bursa under the acromion. The humeral head has no or little superior translation ($\leq$ 3 mm) during scapular plane abduction (Poppen and Walker, 1976; Deutsch et al., 1996; Paletta et al., 1997) and inferior slide (Poppen and Walker, 1976, Soslowsky et al., 1992; Deutsch et al., 1996; Chen et al., 1999; Graichen et al., 2000) could decrease this translation leaving space for the supraspinatus and the bursa to prevent impingement.

The forces transferred to the capsule during contraction of the supraspinatus muscle provide dynamic stability of the glenohumeral joint. 120° or slightly more of abduction in a total of 180° shoulder abduction occurs in the glenohumeral joint while scapular upward rotation is needed for the remained 60° to be completed. Scapulothoracic upward rotation is achieved by sternoclavicular joint elevation, and acromioclavicular joint slide and rotation. Decreased motion in any of the contributing joint results in increased motion of the other joint (Pronk et al., 1993). Without full scapulothoracic motion, one third of full shoulder elevation motion could not be completed (Inman et al., 1996). Scapular upward rotation provides sufficient length of the deltoid muscle for its contraction during wide range of the shoulder elevation. Otherwise, the deltoid muscle shortens maximally at 90° of shoulder abduction loosing the chance to maintain its contraction for the rest of the motion. Moreover, to achieve full abduction, there must be 35°—40° of external rotation, for the clearance of greater tubercle under the coracoacromial arch (Stokdijk et al., 2003; Ludewig et al., 2009; Matsuki et al., 2012). Maximum abduction is found to occur in scapular plane without the need to external rotation (Saha, 1983). This wider range of motion is due to lack of the capsular tension in this plane. Furthermore, the risk of impingement is low because the apex of the greater tubercle is placed under the relatively high point of the coracoacromial arch.

Subacromial impingement syndrome and scapulohumeral rhythm

Subacromial impingement syndrome is the most common musculoskeletal shoulder condition presumed to contribute to the development or progression of rotator cuff disease (Michener et al., 2003). Subacromial impingement is defined as the persistent or repeated compression and abrasion of the rotator cuff tendons or tendon of the long head of the biceps brachii muscle mostly beneath the anterior acromion but also beneath any aspect of the coracoacromial arch including acromial undersurface, coracoacromial ligament, and the undersurface of the acromioclavicular joint (Neer, 1983, Graichen et al., 2001).

Excess or reduced motion and abnormal motion patterns at particular ranges of the shoulder motions (Michener et al., 2003), and anatomic abnormalities of the acromion or humerus (Zuckerman et al., 1992) are some of the proposed mechanisms that lead impingement (Ludewig and Braman, 2011). Abnormal scapulothoracic motion during shoulder elevation including decreased upward rotation and posterior tilting, and increased internal rotation could narrow the subacromial space and produce compression of the structures within the subacromial space (Kelley and Clark, 1995; Lukasiewicz et al., 1999; Borstad and Ludewig 2005; Forthomme et al., 2008; Ludewig and Reynolds, 2009).

Abnormal scapulohumeral rhythm during shoulder elevation may be another mechanism for the development of the impingement (Cohen and Williams, 1998; Ludewig and Cook, 2000). Scapulohumeral rhythm is defined as the synchronous movement of humeral elevation and scapular upward rotation during shoulder flexion or abduction (Inman et al., 1996; Habechian et al., 2014). During active, voluntary elevation of the healthy shoulder, for every 2° of glenohumeral joint abduction or flexion 1° of upward rotation occurs at the scapulothoracic joint (Inman et al., 1996; McClure et al., 2001) (Fig. 11.26).

The 2:1 ratio between glenohumeral and scapulothoracic motion is apparent after 30° of shoulder abduction and 60° of shoulder flexion and the contribution of the scapulothoracic joint increases in the late range of the elevation. This ratio becomes smaller during scapular plane shoulder elevation (Freedman and Munro, 1966; Poppen and Walker, 1976; Bagg and Forrest, 1988; Graichen et al., 2000; McClure et al., 2001) pointing out either more scapular or less glenohumeral contribution to the movement. After original study on scapulohumeral rhythm by Inman et al. (1992), other authors found variable results (Poppen and Walker 1976; McQuade and Smidt, 1998; Graichen et al., 2000; McClure et al., 2001) probably due to their different methodologies. Another important point is that the muscle problems can influence this ratio because during active motion it is likely to depend on muscle activity. Inman et al., also reported that in the early phase (0°–90°) of shoulder abduction, 60° of glenohumeral joint abduction and 30° of scapulathoracic upward rotation occurs. 20°–25° clavicular elevation at the sternoclavicular joint and 5°–10° of upward rotation with rotational fine tuning at the acromioclavicular joint contributes to this upward rotation (van der Helm and Pronk, 1995; Inman et al., 1996). In the late phase (90°–180°) of shoulder abduction, a second couple of 60° of glenohumeral joint abduction and 30° of scapulathoracic upward rotation motion occurs. This time, 5°–10°

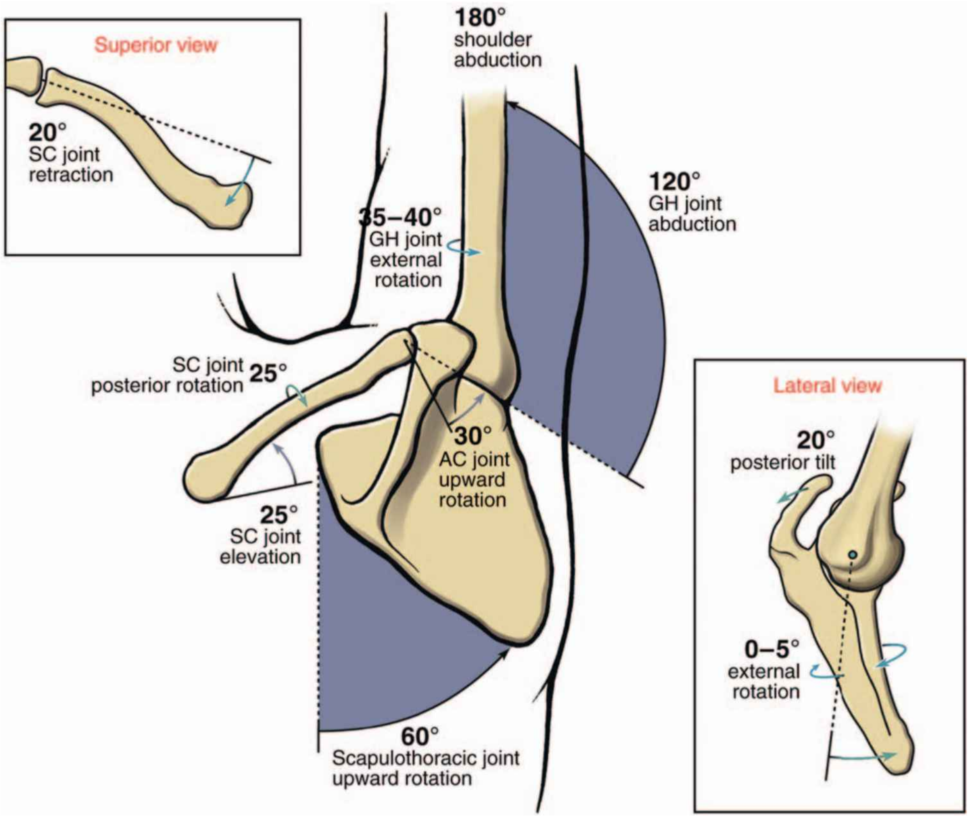

FIGURE 11.26 Scapulohumeral rhythm.

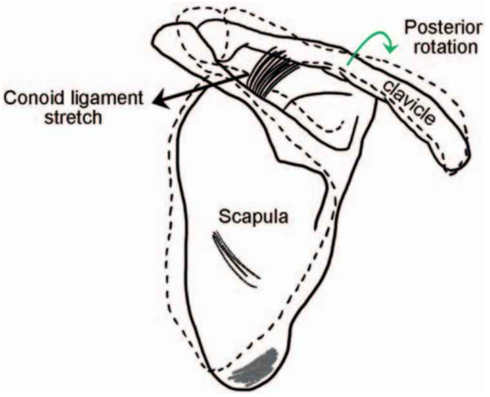

FIGURE 11.27 Upward rotation of the clavicle during shoulder elevation.

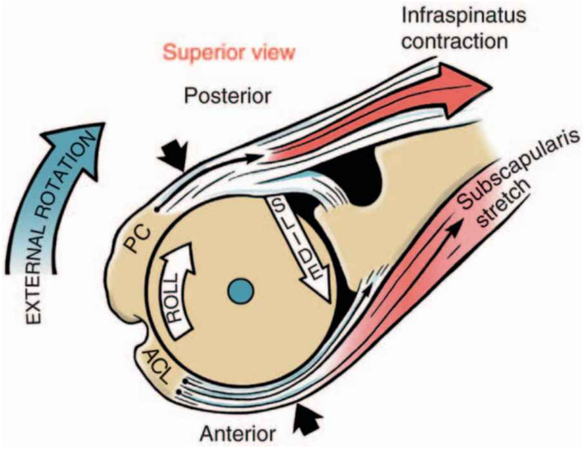

FIGURE 11.28 Arthrokinematics during shoulder external rotation.

clavicular elevation at the sternoclavicular joint and 20°−25° of upward rotation at the acromioclavicular joint contributes to this upward rotation (Inman et al., 1996). The sternoclavicular joint also retracts (20°) and upwardly rotates during shoulder elevation (Inman et al., 1996; McClure et al., 2001; Ludewig et al., 2004b; Giphart et al., 2013; Lawrence et al., 2014a,b). In the very early phase of shoulder abduction, the scapula begins to move away from the clavicle, causing upward rotation at the acromioclavicular joint via pulling of serratus anterior muscle. This situation stretches the conoid portion of the coracoclavicular ligament. Thus, the conoid tubercle of the clavicle moves toward the coracoid process of the scapula and a posterior force on the clavicula, created by the taut ligament, results in a posterior rotation of the clavicle (Inman et al., 1996; Oki et al., 2012; Lawrence et al., 2014a,b). In addition, the crank-shaped clavicle upwardly rotates and completes its external rotation (Fig. 11.27).

About 30°−35° of posterior rotation in the late phase of shoulder abduction unloads the coracoclavicular ligament and remained 30° of scapular upward rotation, which is vital for full shoulder abduction to be completed, occurs.

Muscle weakness or imbalances (Deutsch et al., 1996; Chen et al., 1999; Ludewig and Cook, 2000), poor posture (Kebaetse et al., 1999; Kalra et al., 2010), tightness of the glenohumeral joint capsule (Warner et al., 1990; Tyler et al., 2000; Sizer et al., 2003; Myers et al., 2006), irregularities in acromioclavicular joint, and degeneration of the structures of the subacromial space are also the other mechanisms for the impingement (Michener et al., 2003; Hurov, 2009). As a result of these multiple mechanisms, persistent or repeated compression could cause an inflammatory response resulting in pain and inability to elevate shoulder (Michener et al., 2003). Understanding of normal and abnormal biomechanics of the shoulder, and contributions of sternoclavicular and acromioclavicular joint motions to overall scapulothoracic motions during arm elevation is highly important both for the prevention and the rehabilitation of subacromial impingement.

Internal rotation and external rotation are defined as the axial rotation of the humerus about a vertical axis in the horizontal plane (Fig. 11.24). The humeral head rolls posteriorly and slides anteriorly on the glenoid fossa during external rotation and the reverse arthrokinematics occur during internal rotation (Fig. 11.28).

Full external rotation of the shoulder causes 1−2 mm of posterior translation of the humeral head and anterior slide limits this translation. However, full external rotation without sufficient anterior slide posterior translation of the humeral head is about 38 mm. Since the transverse diameter of the glenoid fossa is about 25 mm, 38 mm posterior translation of the head could lead dislocation. As aforementioned before, the central position of the humeral head is highly important for enhancing dynamic stability with the help of the rotator cuff muscles. For example, contraction of the external rotator muscles tightens the posterior capsule and provides stability during external rotation. In the other hand, taut subscapularis muscle, anterior capsule, middle glenohumeral ligament, and coracohumeral ligament increase the stability.

70°−85° of internal rotation and 70° of external rotation occurs in anatomic position, whereas 90° external rotation can be achieved in 90° of shoulder abduction. Although shoulder rotation occurs almost solely from the glenohumeral joint, protraction of the sternoclavicular joint and abduction, anterior tilting and internal rotation of the scapulothoracic joint are with internal rotation, retraction of the sternoclavicular joint and adduction, posterior tilting, and external rotation of the scapulothoracic joint are with external rotation. In the case of decreased rotation scapulothoracic motion can provide substitution in some degree.

Glenohumeral internal rotation deficit (GIRD)

Posterior or posteroinferior capsular tightness is often demonstrated by a loss of internal rotation in the glenohumeral joint. This loss of internal rotation in the glenohumeral joint is known as glenohumeral internal rotation deficit (GIRD) (Burkhart et al., 2003a,b). It is a common problem in dominant shoulders of the overhead athletes, often seen in baseball pitchers, with shoulder impingement (Kugler et al., 1996; Tyler et al., 2000; Wilk et al., 2011). It's also seen in people with external impingement of the shoulder. Anatomical GIRD is defined as normal in overhead athletes, which is characterized by a loss of internal rotation of less than 18°–20° with symmetrical total rotational motion (TROM) bilaterally (Manske et al., 2013). Pathologic GIRD is defined as a loss of internal rotation greater than or equal to 18°–20° compared to the contralateral side (Burkhart et al., 2003a,b). Burkhart et al., also pointed out that the corresponding asymmetry in TROM greater than 5° compared to uninvolved arm supports the existence of the GIRD. Activities such as repetitive throwing are the leading causes of pathologic GIRD. GIRD is related with more superior and anterior migration of the humeral head and altered kinematics of the glenohumeral as well as the scapulothoracic joint, possibly leading shoulder impingement (Harryman et al., 1990; Muraki et al., 2012).

Closed pack position of the glenohumeral joint is 90° of abduction and full external rotation. 30–50° of abduction, flexion and internal rotation and 30° of horizontal adduction is the loose pack position of the joint. Capsular pattern of the joint, a series of limitations of the joint movement due to the joint capsule is external rotation > abduction > internal rotation.

Osteokinematics at the glenohumeral joint
1. Flexion/Extension
2. Abduction/Adduction
3. Internal/External Rotation

Athrokinematics at the glenohumeral joint
1. Spin (pure flexion/extension)
2. Inferior slide, Superior roll (abduction)
3. Superior slide, Inferior roll (adduction)
4. Posterior slide, Anterior roll (internal rotation)
Anterior slide, Posterior roll (external rotation)

Normal range of motion in shoulder and shoulder range of motion required in activities of daily living

Normal values of shoulder range of motion is generally accepted as 180° of shoulder flexion, 55°–60° of shoulder extension, 180° of shoulder abduction, 70°–85° of internal rotation and 70°–90° external rotation. However, reported normal values of range of motion in the literature are not unequivocal attributable to their different methodologies and sample choices (Boone and Azen, 1979; Murray et al., 1985; Barnes et al., 2001).

Namdari et al., defined functional shoulder range of motion at glenohumeral joint for ADL (Namdari et al., 2012). They reported average shoulder motions required to perform the 10 functional tasks, which are listed at Table 11.2.

In Magermans et al.'s study it was reported that 90° of glenohumeral flexion or abduction, 70° of external rotation of the shoulder, and 35° of scapular upward rotation was needed to comb hair (Magermans et al., 2005). Their result for glenohumeral flexion needed to comb hair indicates less range of motion than Namdari et al.'s results.

It was stated that approximately 120° of forward elevation, 45° of extension, 130° of abduction, 115° of cross-body adduction, 60° of external rotation, and 100° of internal rotation is required to complete almost all activities of daily living (Namdari et al., 2012).

Muscles of shoulder complex

Proximal stabilizers

Axioscapular and axioclavicular muscles

Axioscapular and axioclavicular muscles have attachments on the spine, ribs, cranium, and the scapula or clavicle. Pectoralis minor and subclavius muscles are located on the anterior surface of the trunk while trapezius (upper, middle, and lower portions), serratus anterior, levator scapulae, rhomboid major and minor muscles are located posteriorly. These muscles position the scapula and clavicle by moving the sternoclavicular and scapulothoracic joints, with resulting motion at the acromioclavicular joint. Axioscapular muscles provide scapular stabilization during scapular movements.

The scapulothoracic joint elevators (Fig. 11.29).

Trapezius muscle (upper portion)

Origin: External occipital proturberance, medial third of the superior nuchal line, the ligamentum nuchae, the spinous process of C7.

Insertion: Lateral third of the clavicle, the medial aspect of the acromion process of the scapula.

Innervation: Spinal accessory nerve (Cranial nerve XI), ventral rami C2–C4.

Blood Supply: Branches from the thyrocervical trunk.

Action: The primary actions of the upper trapezius are elevation of sternoclavicular joint and scapular elevation, upward rotation, and adduction. The muscle is highly active during active elevation of the shoulder, shoulder shrug and scapular adduction (Brandell 1970; Bull et al., 1985, 1986, 1989, 1990). Moreover, it contracts

TABLE 11.2 Average range of motion in dominant and nondominant arms while performing selected activities of daily living.

Activities of daily living	Measured humeral motion	Maximum motion to complete the task[a]	
		Dominant arm	Non-dominant arm
1. Place a can of soup can on an overhead shelf without bending the elbow	Flexion	105°	108°
	External rotation	34°	31°
2. Reach the small of one's back to tuck in one's shirt with one's hand	Extensionn	45°	46°
	Internal rotation	88°	87°
3. Wash the middle of one's back/unhook one's own bra (middle of back)	Extensionn	47°	46°
	Internal rotation	99°	102°
4. Wash the back of the opposite shoulder	Flexion	95°	93°
	Adduction	116°	116°
5. Place hand behind one's head with the elbow held straight out to the side	Abduction	127°	129°
	External rotation (arm at 90°)	61°	56°
6. Comb hair	Flexion	108°	109°
	Adduction	86°	91°
7. Place a can of soup on a shelf at shoulder level without bending the elbow	Flexion	121°	126°
	External rotation	38°	32°
8. Place a 1-gallon container (8–10 lbs, 3.5–4.5 kg) on a shelf at shoulder level without bending the elbow	Flexion	106°	107°
	External rotation	39°	38°
9. Reach a shelf above one's head without bending the elbow	Flexion	119°	123°
	External rotation	29°	26°
10. Place a 1-gallon container on an overhead shelf without bending the elbow	Flexion	120°	127°
	External rotation	42°	42°

[a] *Actual values of range of motion from Namdari et al.'s study (Namdari et al., 2012) are rounded off to the nearest integer.*

eccentrically during lowering the arm (Bull et al., 1985, 1989). Its secondary actions are assisting with elevation and lateral flexion of the cervical spine, and contralateral rotation of the head and cervical spine when acting unilaterally. These actions point out that the muscle has a role in neck and shoulder posture (Inman et al., 1996; Johnson et al., 1996).

Problems in the upper trapezius muscle: Injury of the cranial nerve XI can cause *paralysis* of the upper trapezius and depression and downward rotation of the scapulothoracic joint can lead sternoclavicular joint dislocation. Another problem related to paralysis of the upper trapezius is possible inferior subluxation of the glenohumeral joint due to loss of upward rotation position of the glenoid fossa, which is vital for static stabilization. Although it is

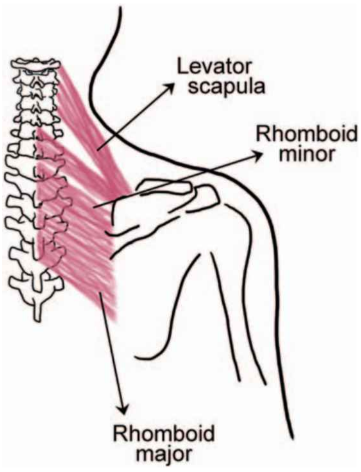

FIGURE 11.29 The Upper trapezius, levator scapulae, and rhomboids.

not fully clear, weakness of upper trapezius may change scapular position and cause postural problems (Oatis, 2009). Deteriorated scapular kinematics, especially increased protraction, over active upper trapezius and decreased or delayed activity of scapular stabilizers such as latissimus dorsi and serratus anterior are presumably related to scapular dyskinesis (Ludewig and Cook, 2000; Kibler et al., 2013; Kibler and Sciascia, 2013). Arm elevation exercises that commonly prescribed in either internal rotation (empty can exercise) or external rotation (full can exercise) to improve symptoms of subacromial impingement syndrome. However it was found that the empty can exercise was associated with more pain and scapular positions that have been reported to decrease the subacromial space. Moreover, scapular muscle activity including upper trapezius was higher with the empty can exercise, which may be an attempt to control the impingement-related scapular motion (Timmons et al., 2016). Therefore exercises that provide optimum rate of upper trapezius activity against middle trapezius, lower trapezius, and serratus anterior activity are still hot topic of the recent studies (Cools et al., 2007; De Mey et al., 2009, 2012, 2013, 2014; Maenhout et al., 2010). Yeşilyaprak et al., found that having a shorter upper trapezius length substantially increased the likelihood of having visually observable scapular dyskinesis and recommended routine assessment of the length of this muscle in scapular examination (Yesilyaprak et al., 2016). The effect of short upper trapezius muscle on scapular motions may be related first; to a lesser serratus anterior activation, leading to lesser posterior tilt and upward rotation of the scapula (Forthomme et al., 2008; Ludewig and Reynolds 2009; Cools et al., 2014). Second; it may increase elevation of the scapula through greater clavicular elevation, leading to more anterior tilt (Ludewig and Reynolds, 2009; Phadke et al., 2009). Upper trapezius tightness or shortness is also associated with elevated shoulders, asymmetrical head positions, and restricted range of motion in the head and the neck.

Levator scapulae muscle

Origin: Posterior tubercles of transverse processes of C1–C4 vertebrae.

Insertion: Superior part of medial border of scapula.

Innervation: Dorsal scapular (C5) and C3, C4 nerves.

Blood Supply: Dorsal scapular artery.

Action: The primary actions of levator scapulae muscle are elevation, adduction of the scapula and tilting the glenoid cavity inferiorly by rotating the scapula downwardly. It rotates the cervical spine ipsilaterally. It also supports upright position of the shoulder complex (Inman et al., 1996; Johnson et al., 1996). Levator scapulae muscle and rhomboid muscles show great activity when reaching a back pocket (Stefko et al., 1997).

Problems in the levator scapulae muscle: As the levator scapulae together with the rhomboids supports upright position of the shoulder complex, weakness of these muscle groups can cause rounded shoulder posture. Tight levator scapulae also contributes rounded shoulder posture via affecting scapular kinematics by elevating, adducting, and downwardly rotating the scapula.

Rhomboid major and minor muscles

Origin: Rhomboid Major: Spinous processes and supraspinous ligaments of T2–T5 vertebrae.

Rhomboid Minor: Nuchal ligament and spinous processes of C7 and T1 vertebrae.

Insertion: Rhomboid Major: Medial border of the scapula from the root of the spine to the inferior angle.

Rhomboid Minor: Superior part of medial border of the scapula at the level of the scapular spine.

Innervation: Dorsal scapular nerve (C4, C5).

Blood Supply: Dorsal scapular artery.

Action: The primary actions of rhomboid muscles are elevation, adduction and downward rotation of the scapula. It fixes scapula to the thoracic wall and support upright position of the shoulder complex (Inman et al., 1996; Johnson et al., 1996; Palmerud et al., 1998). It also rotates the cervical spine contralaterally. These muscles together with levator scapulae muscle show great activity when reaching a back pocket (Stefko et al., 1997) and they are somewhat active during shoulder elevation (Inman et al., 1996).

Problems in the rhomboid muscles: As it was aforementioned above, rounded shoulder posture can be seen in case rhomboid weakness. In contrast, tightness of levator scapulae muscle and rhomboid muscles was also regarded as responsible from rounded shoulder posture. The proposed mechanism underlying this suggestion is the actions of the muscles. Elevation, adduction, and downward rotation of the scapula tilts the glenoid cavity inferiorly by rotating the scapula in downward and anterior directions. Activities such as rowing can be impaired, as well.

The scapulothoracic joint depressors (Fig. 11.30).

Trapezius muscle (lower portion)

Origin: Spinous processes of T6–T12.

Insertion: Tubercles of the apex of the scapular spine.

Innervation: Spinal accessory nerve (Cranial nerve XI), ventral rami C2–C4.

Blood Supply: Branches from the thyrocervical trunk.

Action: The primary action of the upper trapezius is upward rotation and depression of the scapula. The axis for upward-downward rotation of the scapula lies lateral to the scapular attachment of the lower trapezius muscle causing an inferior pull to the medial aspect of the scapular spine and rotates the scapula upwardly. Simultaneous

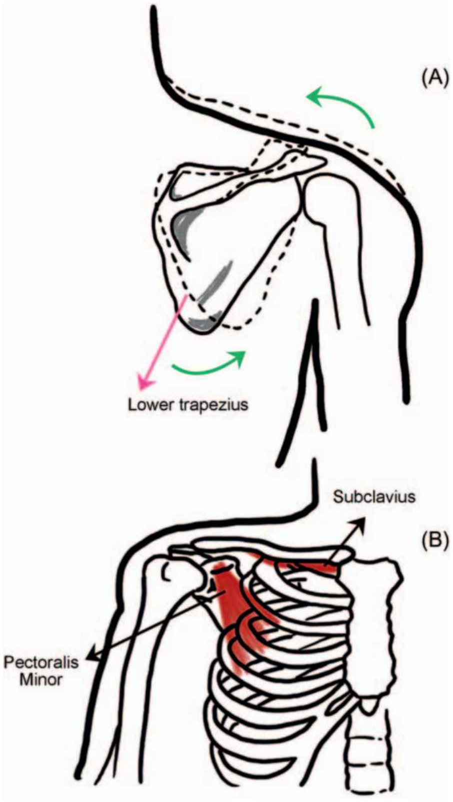

FIGURE 11.30 (A) The lower trapezius, (B) the Pectoralis minor, and Subclavius.

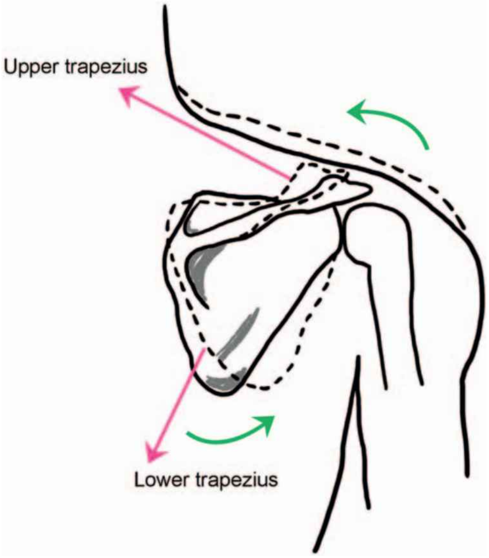

FIGURE 11.31 Anatomical force couple, the upper and lower trapezius muscles.

opposite activity of the upper and lower trapezius muscles, anatomical force couple, creates stability with elevation and depression, respectively, when upwardly rotating the scapula (Fig. 11.31).

As opposed to upper trapezius, which is more active during the initiation of the shoulder abduction, lower trapezius increased its activity at the later phase of the abduction (Bagg and Forrest, 1988).

Problems in the lower trapezius muscle: Weakness of lower trapezius may deteriorate scapular stabilization during contraction of the other scapular upward rotators.

Pectoralis minor muscle

Origin: The anterior surfaces and superior borders of the 3rd to 5th ribs near their costal cartilages.

Insertion: Medial border and superior surface of the coracoid process of scapula.

Innervation: Medial pectoral nerves; clavicular head (C8 and T1).

Blood Supply: Pectoral branch of the thoracoacromial trunk.

Action: The actions of the pectoralis minor muscle are anterior tilt, internal rotation, and downward rotation of the scapula (Ludewig and Cook, 2000). It stabilizes the scapula by drawing it inferiorly and anteriorly against thoracic wall. As it tilts the scapula anteriorly it also cause elevation of the scapula during its isolated contraction. In contrast, the line of pull of the pectoralis minor muscle pulls the coracoid process down and during combined muscle actions to prevent anterior tilt of the scapula caused by the pectoralis minor pull in inferior direction, pectoralis minor muscle also helps other muscles of scapular depression. This situation contributes the stabilization of the scapula and shoulder complex against the elevation. This is important for activities such as chair press-up when an elevation force is applied on the scapula through the upper extremity in order to raise thorax. Because of the position of the muscle on the anterior aspect of the thorax its pull on the coracoid process causes anterior slide of the scapula causing the scapula to abduct. Simultaneous opposite scapular abduction and adduction activity of the pectoralis minor muscle and levator scapulae and rhomboids, another anatomical force couple, contribute to the balanced scapular downward rotation (Fig. 11.32).

Problems in the pectoralis minor muscle: Short pectoralis minor can restrict normal scapular movement, resulting in a more anteriorly tilted (could also be less posterior tilt), protracted, internally rotated, and elevated scapula during arm elevation (Borstad and Ludewig, 2005; Ludewig and Reynolds, 2009; Ellenbecker and, Cools 2010; Kibler et al., 2013; Kibler and Sciascia, 2013). This can narrow the subacromial space, leading to shoulder impingement (Borstad and Ludewig, 2005). Short pectoralis minor can also be associated with decreased muscle activity of serratus anterior and lower trapezius muscles (Kibler et al., 2013). Recent research has demonstrated a negative relationship between pectoralis minor length and

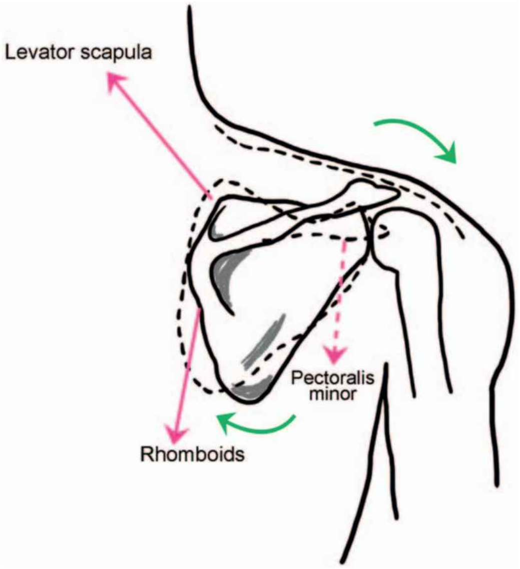

FIGURE 11.32 Anatomical force couple, the rhomboids, levator scapulae, and Pectoralis minor muscles.

scapular dyskinesis (Forthomme et al., 2008; Ludewig and Reynolds, 2009; Kibler and Sciascia, 2010; Kibler and Sciascia, 2013; Cools et al., 2014). It was also determined that the shortening of pectoralis minor length increases the likelihood of exhibiting visually observable scapular dyskinesis. Including the assessment of the pectoralis minor muscle length as a routine part of the scapular examination may aid treatment decision-making in visually observable scapular dyskinesis (Yesilyaprak et al., 2016). Additionally, it has been found that individuals with forward head and rounded shoulder posture display altered scapular motions likely due to shorter pectoralis minor length (Thigpen et al., 2010).

Subclavius muscle

Origin: The first rib (border between the bone and cartilage, just anterior to the costoclavicular ligament).

Insertion: The lower surface of the middle clavicle.

Innervation: Subclavian branch of brachial plexus (C5, C6).

Blood Supply: Clavicular branch from the thoracoacromial artery and the suprascapular artery.

Action: The action of the subclavius muscle is depression of the clavicle and elevation of the first rib. It stabilizes the clavicle in the sternoclavicular joint during movements of the shoulder and arm (Reis et al., 1979).

Problems in the subclavius muscle: Tightness of subclavius muscle limits elevation at the sternoclavicular joint leading insufficient scapulothoracic joint upward rotation that results in decreased shoulder movements. Pain below the clavicle or in the upper arm could be associated with subclavius muscle. Subclavius tightness can also restrict circulation to the arm and hand causing tingling and numbness. Dysfunction in subclavius muscle can mimic the symptoms of thoracic outlet syndrome.

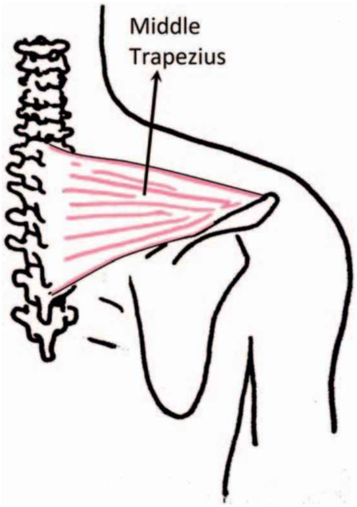

FIGURE 11.33 The middle trapezius.

The scapulothoracic joint adductors

Trapezius muscle (middle portion) (Fig. 11.33)

Origin: Spinous processes of T1–T5.

Insertion: Medial edge of the superior surface of the acromion process of the scapula and the superior edge of the scapular spine.

Innervation: Spinal accessory nerve (Cranial nerve XI), ventral rami C2–C4.

Blood Supply: Branches from the thyrocervical trunk.

Action: The primary action of the upper trapezius is adduction of scapula. The muscle is also active during shoulder shrug (Johnson and Pandyan, 2005). Rhomboids and the lower trapezius muscles are the secondary adductors.

Problems in middle trapezius muscle: Middle trapezius weakness decreases scapular adduction strength and cause difficulties in contracting scapulohumeral muscles and in exerting their forces due to unstable scapula. Arm elevation in the fontal plane is very difficult in case of middle trapezius paralysis due to insufficient adduction of the scapula. Cools et al., found that overhead athletes with shoulder impingement syndrome have delayed onset of middle and lower trapezius fibers in response to a sudden downward movement (Cools et al., 2003).

The scapulothoracic joint abductors (Fig. 11.34)

Serratus anterior muscle

Origin: Anterolateral surfaces and superior borders of the first 8–10 ribs and the intercostal muscles in between.

Insertion: Anterior surface of the medial border of the scapula from the superior to the inferior angles.

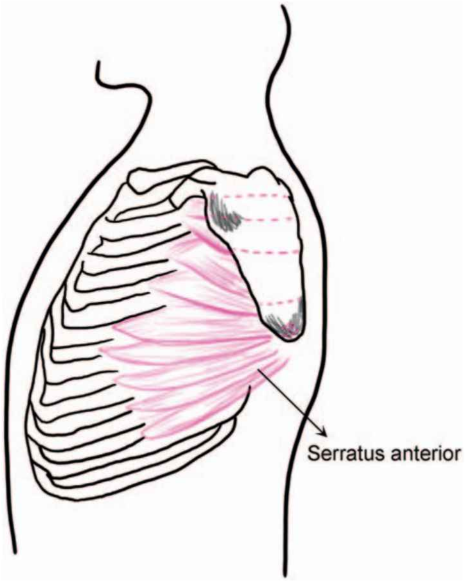

FIGURE 11.34 The Serratus anterior.

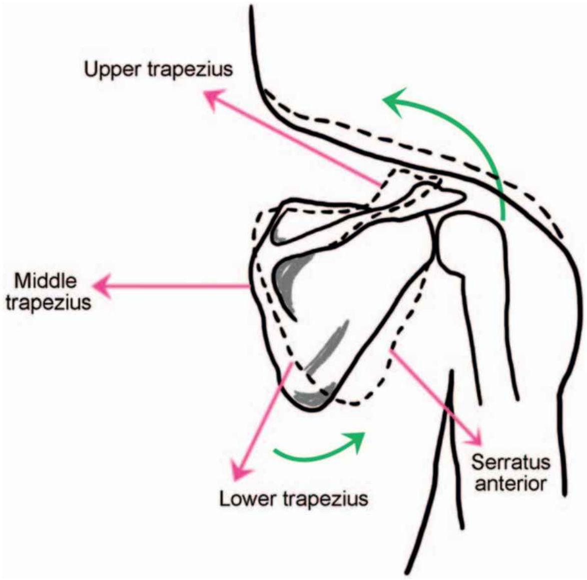

FIGURE 11.35 Anatomical force couple, trapezius and Serratus anterior muscles.

Innervation: Long thoracic nerve (C5–7).

Blood Supply: Circumflex scapular artery.

Action: The primary action of the serratus anterior is abduction of scapula. It elevates and upwardly rotates the scapula and stabilizes vertebral border of scapula. Authors describing serratus anterior as two parts stated that the upper portion elevates the scapula while the lower portion abducts and upwardly rotates it (Bull et al., 1989, Inman et al., 1996). Both the trapezius and serratus anterior muscles, another anatomical force couple, upwardly rotate the scapula, while the trapezius adducts and the serratus anterior abducts the scapula ensuring balanced scapular motion during shoulder elevation (Arwert et al., 1997) (Fig. 11.35).

The serratus anterior is active during the entire range of shoulder elevation. The muscle is highly active in forward push, reaching activities, and push up plus and its variations (Moseley et al., 1992; Ludewig et al., 2004a; Maenhout et al., 2010).

Problems in serratus anterior muscle: Injury of the long thoracic nerve can cause *paralysis* of the serratus anterior muscle (Watson and Schenkman, 1995). Serratus anterior weakness decreases scapular abduction, upward rotation, and elevation. Elevating arm above 90° of abduction is not possible. Insufficient upward rotation of the scapula due to weak serratus anterior causes downward rotation of the scapula with the contractions of deltoid and supraspinatus muscles. Thus, scapulohumeral abductor muscles shorten early loosing the chance to perform their maximum force potential for the rest of the motion. Weakness in serratus anterior or middle trapezius deteriorates the scapular balance and changes the resting position of the scapula in the direction of adduction or abduction, respectively. Pushing forward against an object like a revolving door becomes difficult due to reaction force that tends to adduct the scapula. Similarly, elevating the arm especially against resistance becomes difficult, too. Since the origin of the serratus anterior muscle is at the anterior surface of the medial border of the scapula, forces that adduct the scapula also cause a posterior protrusion of the medial aspect of the scapula from the thorax. This observable postural change is called "scapular winging" (Fig. 11.36).

Decreased activity of the serratus anterior as well as lower trapezius as lower stabilizers of the scapula can cause abnormal scapular motions and contribute common musculoskeletal problems such as shoulder impingement to occur (Falla et al., 2007; Kibler et al., 2012, 2013).

Distal mobilizers

Muscles called distal mobilizers have attachments on the scapula and/or clavicle and the humerus or forearm. Scapular stabilization successfully created by the proximal stabilizers is needed in order to distal mobilizers to move shoulder effectively.

Scapulohumeral muscles

The deltoid, coracobrachialis, teres major, and the rotator cuff muscles; the supraspinatus, infraspinatus, teres minor, subscapularis, and long head of the biceps brachii are the scapulohumeral muscles (Fig. 11.37).

Motion with dynamic stabilization in the glenohumeral joint is provided by these muscles. Their contribution to the dynamic joint stabilization could be explained with such mechanisms: passive muscle tension, active compression created by rotator cuff muscle contraction, restraint effect of shortened muscles during contraction, and joint forces directed to the center of the glenoid cavity by coordinated muscle actions (Abboud and Soslowsky, 2002).

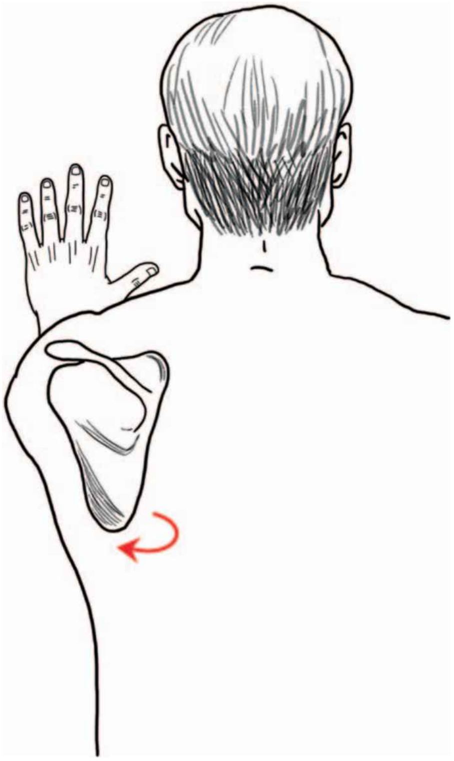

FIGURE 11.36 Scapular winging during pushing forward against the wall.

The arm elevators

Deltoid muscle (anterior and middle portion) (Fig. 11.38) Origin: Anterior portion: Anterior-superior border of the lateral third of the clavicle.

Middle portion: Lateral-superior border of the acromion of the scapula.

Insertion: Deltoid tuberosity.

Innervation: Axillary nerve (C5, 6).

Blood Supply: Posterior circumflex humeral artery from the axillary artery and the deltoid branch of the thoracoacromial artery.

Action: The primary action of the anterior deltoid is flexion of humerus. The deltoid and pectoralis minor (clavicular portion) muscles were stated as prime movers of the arm due to their mechanical advantages (Inman et al., 1996). The mechanical advantage of the deltoid muscle is a result of its improved contractile length via expansion of the acromion and distal insertion (Inman et al., 1996). Although the role of the anterior deltoid in internal rotation of humerus seems conflicting (Kronberg et al., 1990b; Kuechle et al., 2000) still it's accepted as an internal rotator. The anterior deltoid is generally recruited before the clavicular portion of the pectoralis major muscle during shoulder elevation (Jackson et al., 1977).

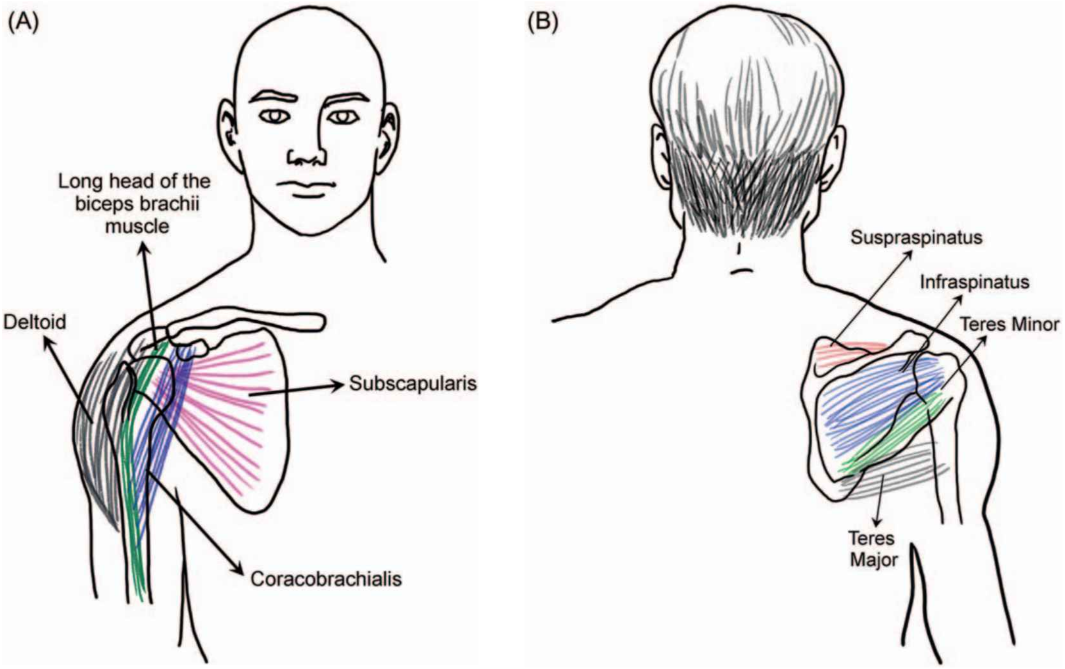

FIGURE 11.37 (A) The deltoid, coracobrachialis, long head of the biceps brachii, and subscapularis, (B) teres major, the supraspinatus, infraspinatus, and teres minor.

The role of the anterior deltoid in shoulder horizontal adduction is still debatable.

The primary action of the middle deltoid is abduction of the humerus. The middle deltoid is multipennate (Gray et al., 1995) and has larger cross-sectional area than the other parts of the deltoid (Langenderfer et al., 2004). These futures of the muscle lead great potential for force production. The deltoid is most active during mid range of shoulder abduction (Kronberg et al., 1990b), while it also shows some activity during shoulder flexion (Arwert et al., 1997).

Problems in anterior and middle deltoid muscles: Anterior and middle deltoid weaknesses cause weakness primarily in shoulder flexion and abduction, respectively. As a whole the muscle is fatigue-resistant and this might be the reason why deltoid doesn't contribute shoulder pathologies as much as other musculatures do (Hagberg, 1981). Nevertheless, the pathomechanics of shoulder impingement may involve anatomical force couples: deltoid/rotator cuff muscles and scapular rotators (Page, 2011). Downward compressive force created by the rotator cuff muscles neutralizes the upwardly directed shear forces of the deltoid (Payne et al., 1997). Muscle imbalances in the deltoid and rotator cuff muscles can cause compression within the subacromial space (Jerosch et al., 1989; Payne et al., 1997).

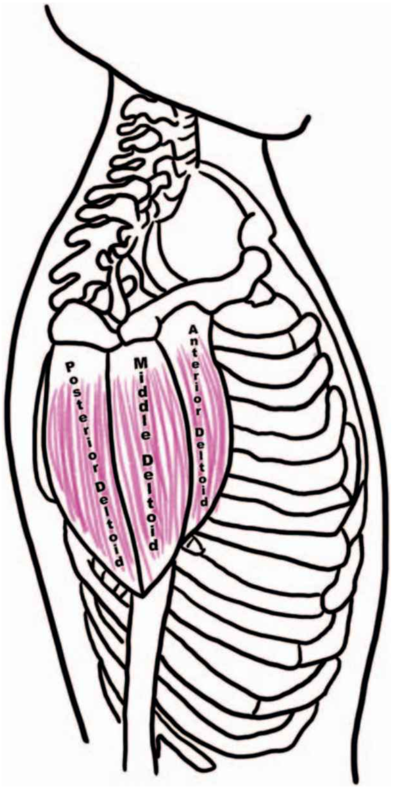

FIGURE 11.38 The deltoid.

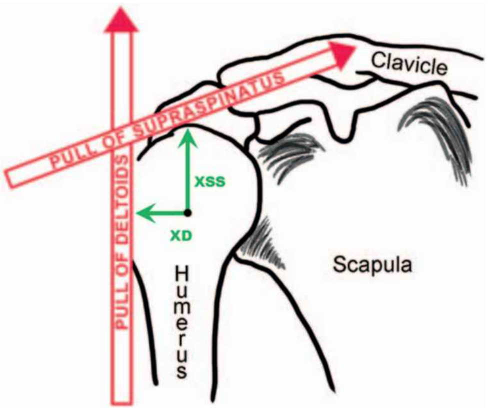

FIGURE 11.39 Moment arms of the deltoid and supraspinatus muscles during shoulder abduction.

Supraspinatus muscle

Origin: Medial two thirds of the supraspinous fossa of the scapula.

Insertion: Superior facet on greater tuberosity of the humerus and the glenohumeral joint capsule.

Innervation: Suprascapular nerve (C4–6).

Blood Supply: Suprascapular artery.

Action: The primary action of the supraspinatus is initiation and assisting deltoid in abduction of arm working with other rotator cuff muscles (Kronberg et al., 1990b, Inman et al., 1996). The line of pull of the supraspinatus is similar to middle deltoid's line of pull. As middle deltoid supraspinatus is active during initiation of the shoulder elevation and most active during mid range of shoulder abduction (Gray et al., 1995). At initial ranges of the shoulder abduction the deltoid has a small moment arm (1.42 cm) whereas the supraspinatus has a larger moment arm (2.6 cm) (Otis et al., 1994) (Fig. 11.39).

Additionally, superiorly directed line of pull of the middle deltoid causes superior translation of the humeral head. In contrast, the supraspinatus produces abduction via its mechanical advantage and gives dynamic stability to the glenohumeral joint by compressing the glenoid cavity (Soslowsky et al., 1997). All rotator cuff muscles work together in order to compensate the lack of stability at the glenohumeral joint during wide range of shoulder motion. The anterior portion of the supraspinatus is most favorably oriented to apply joint compression during arm elevation. The compression force of the supraspinatus muscle stabilizes the humeral head into the glenoid cavity while superior directed line of pull of the deltoid muscle rolls the humeral head into superior direction. Approximately 9 mm superior translation of the humerus was reported during arm elevation reaching up to 90° (Wuelker et al., 1994). As the deltoid and rotator cuff muscles are anatomical force couples of shoulder

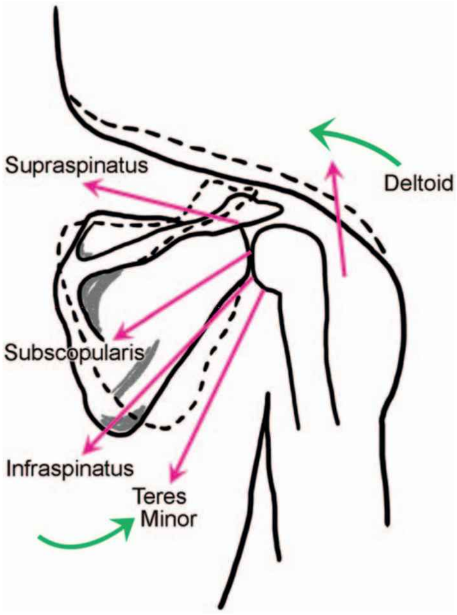

FIGURE 11.40 Anatomical force couple, deltoid and rotator cuff muscles.

abduction, other rotator cuff muscles decrease excessive superior translation of the humeral head creating an inferior force (Fig. 11.40).

During activities such as throwing a ball including humeral external rotation and abduction, rotator cuff muscles contract to help static stabilizers in preventing excessive anterior displacement of the humeral head. The opposite medial pull of the horizontally oriented supraspinatus muscle against lateral movement of the humeral head contributes prevention of inferior displacement of the humerus. This function of the supraspinatus is facilitated by the upward tilt of the glenoid fossa. The muscle is active during shoulder abduction when the shoulder positioned in either internal or external rotation (Worrell et al., 1992). However; supraspinatus has been found as more active in shoulder external rotation (Reinold et al., 2004). When the moment arms analyzed, posterior and anterior portions of the supraspinatus contribute external and internal rotation, respectively (Moskowitz and Rashkoff, 1989; Kuechle et al., 2000).

Problems in supraspinatus muscle: Weakness of the supraspinatus causes weakness in shoulder abduction (Van and Mulder, 1963). In case of paralyzed deltoid, the supraspinatus muscle still can perform full shoulder abduction but with a reduced torque whereas full shoulder abduction is not possible without intact supraspinatus. Supraspinatus weakness or paralysis can cause inferior subluxation of the glenohumeral joint. Excessive translation of the humeral head due to inadequate work of rotator cuff muscle to keep the humeral head centered is related with most of the shoulder disorders. In this case, the deltoid overpowers the rotator cuff and cause superior migration (Chopp and Dickerson, 2012) of the humeral head, thus impinging the rotator cuff muscles between the humeral head and the acromion. Reasons of supraspinatus weakness can be mechanical disruption of the supraspinatus tendon or pain induced inhibition of its contraction. The suprasinatus tendon is at highest risk for injury because it is the most likely to contact the acromion when the humerus is abducted to 90° and internally rotated 45° (Graichen et al., 2000). High forces applied supraspinatus over years causes degeneration of the tendon and may lead rotator cuff tears (Graichen et al., 2000). Severely damaged rotator cuff tendons can completely disrupt arthrokinematics of the glenohumeral joint leading frozen shoulder. Michener et al., reported that compared to healthy shoulders, shoulders with subacromial impingement syndrome had thicker supraspinatus tendon providing evidence of an intrinsic mechanism and the supraspinatus tendon occupied a greater percentage of the subacromial space (Michener et al., 2015).

Coracobrachialis muscle

Origin: Tip of the coracoid process of the scapula.

Insertion: Middle third of the medial surface of the humerus.

Innervation: Musculocutaneous nerve (C5–7).

Blood Supply: Muscular branches of brachial artery.

Action: The primary action of the coracobrachialis is flexion of the shoulder (Bassett et al., 1990).

Problems in coracobrachialis muscle: Weakness of the coracobrachialis decreases shoulder flexion strength.

Biceps brachii (long head) muscle

Origin: Supraglenoid tubercle of the scapula. The muscle may also attach to the anterosuperior part of the glenoid labrum.

Insertion: Tuberosity of the radius and deep fascia of the forearm via bicipital aponeurosis.

Innervation: Musculocutaneous nerve (C5, 6).

Blood Supply: Muscular branches of brachial artery.

Action: The primary actions of the long head of the biceps brachii are supinating the forearm and, when it is supine, flexing the forearm. The role of the long head of the biceps brachii in shoulder movements is glenohumeral joint flexion (Borstad, 2006) and stabilization of the shoulder (Brandell, 1970; Bassett et al., 1990; Kramer and Ng, 1996; Makhsous et al., 1999; Alexander et al., 2013). Its contribution to the dynamic stability of the shoulder could be explained by its compression potential via the position of the proximal end of its tendon parallel to supraspinatus muscle. Thus, it can help limiting the excessive translations of the humeral head. It seems that the importance of the biceps brachii becomes prominent in case of decreased capsuloligamentous stability (Itoi et al., 1993).

Both long and short heads of the biceps brachii decreases anterior translation of the humeral head under loaded conditions at 60° or 90° of shoulder external rotation and abduction. Additionally, the role of the biceps in glenohumeral joint stability was revealed with reported anterior and posterior compressive forces during external and internal rotation, respectively (Pagnani et al., 1996).

Problems in long head of the biceps muscle: Weakness of the long head of the biceps causes slight decrease in shoulder flexion strength. However, weakness can cause instability at the glenohumeral joint and leads rotator cuff disease considering aforementioned roles of the muscle in the shoulder. As it is a biarticular muscle tightness of the biceps brachii could affect both shoulder and elbow range of motion, interdependently.

Infraspinatus muscle

Origin: Medial two thirds of the infraspinous fossa of scapula.

Insertion: Middle facet on greater tuberosity of humerus and the glenohumeral joint capsule.

Innervation: Suprascapular nerve (C5–6).

Blood Supply: Suprascapular and circumflex scapular arteries.

Action: The primary action of the infraspinatus is external rotation of the arm and stabilization of the shoulder via holding the humeral head in the glenoid fossa (Gray et al., 1995). It supports the glenohumeral ligaments helping to humeral head to be aligned in more central position to enhance dynamic stability. The muscle is active during shoulder abduction (Otis et al., 1994; Kuechle et al., 2000) and shoulder horizontal abduction (Otis et al., 1994; Arwert et al., 1997; Kuechle et al., 2000). It works with other rotator cuff muscles during shoulder elevation (Kronberg et al., 1990b; Inman et al., 1996). Infraspinatus and teres minor muscles externally rotate the humerus for the clearance between the greater tubercle and the acromion during frontal plane abduction.

Problems in infraspinatus muscle: Weakness of the infraspinatus causes weakness in shoulder external rotation and instability at the glenohumeral joint. Shoulder muscle strength from high to low was reported as: extensors, adductors, flexors, abductors, internal rotators, and external rotators (Shklar and Dvir, 1995). Although the maximal torque produced by the shoulder external rotator muscles is low due to their small total muscle mass, they still can produce very high velocity contractions. The high forces applied on the infraspinatus during these contractions can damage the muscle and this situation can lead rotator cuff diseases (Hughes and An, 1996). Reddy et al., found that during shoulder elevation between 30° and 60° activity of infraspinatus, subscapularis, and middle deltoid muscles decreased in shoulders with impingement (Reddy et al., 2000). Additionally, the infraspinatus muscle activity significantly depressed during 60° to 90° shoulder elevation. In shoulders with impingement, inferior force vector from the infraspinatus and subscapularis muscles less functional than the superior compressive vector from the supraspinatus muscle. This situation can lead insufficient depression of the humeral head during the critical early phase of shoulder elevation in people with subacromial impingement syndrome.

Teres minor muscle

Origin: Superior two thirds of the lateral border of scapula.

Insertion: Inferior facet on greater tuberosity of humerus and the glenohumeral joint capsule.

Innervation: Axillary nerve (C5–6).

Blood Supply: Subscapular and circumflex scapular arteries.

Action: The primary action of the teres minor is external rotation of the arm (Gray et al., 1995). It is also a stabilizer of the glenohumeral joint as the rest of the rotator cuff muscles. It works with the infraspinatus in external rotation of the humerus for the clearance between the greater tubercle and the acromion during frontal plane abduction. These muscles also reduce anterior-inferior capsuloligamentous strain.

Problems in teres minor muscle: Weakness of the teres minor causes weakness in shoulder external rotation and instability at the glenohumeral joint. The decrease in external rotation is not highly significant attributable to its smaller physiological cross-sectional area than the other rotators.

Subscapularis muscle

Origin: Subscapular fossa and the lateral border of the ventral surface of the scapula.

Insertion: Lesser tuberosity of humerus and the glenohumeral joint capsule.

Innervation: Upper and lower subscapular nerves (C5–7).

Blood Supply: Subscapular artery.

Action: The primary action of the subscapularis is internal rotation of the arm (Gray et al., 1995). The subscapularis is also a stabilizer of the glenohumeral joint with holding the humeral head in the glenoid fossa. Contraction of the subscapularis together with the infraspinatus, anatomical force couple, provides stability during 60° to 150° of shoulder abduction (Eberly et al., 2002). Subscapularis, infraspinatus, and teres minor apply inferior force to the humeral head. The subscapularis muscle can have a role in either shoulder adduction or abduction when glenohumeral joint is positioned at internal rotation or external rotation, respectively (Otis et al., 1994; Hughes et al., 1998; Kuechle et al., 2000; Decker et al., 2003). Subscapularis, pectoralis major, anterior deltoid, latissimus dorsi, and teres major are the internal rotators of the shoulder joint. The total muscle mass of the internal rotator muscles is greater than the external rotator muscles. More peak torques and approximately twice as much isometric torque produced by the internal rotator muscles than the external rotator muscles were reported in the literature (Kronberg et al., 1990b; Kramer and Ng, 1996).

Problems in subscapularis muscle: Weakness of the subscapularis causes weakness in shoulder internal rotation. The subscapularis is the strongest stabilizer with its largest amount of muscle mass among rotator cuff muscles and its weakness also causes anterior instability at the glenohumeral joint (Inman et al., 1996). Tightness or trigger points within the subscapularis muscle may lead trigger points in other rotator cuff muscles that may result in glenohumeral joint restriction (Donatelli, 2012).

The arm adductors

Deltoid muscle (posterior portion) (Fig. 11.37) Origin: Inferior edge of the scapular spine.

Insertion: Deltoid tuberosity.

Innervation: Axillary nerve (C5, 6).

Blood Supply: Posterior circumflex humeral artery from the axillary artery and the deltoid branch of the thoracoacromial artery.

Action: The posterior deltoid is highly active in shoulder extension (Williams 1949; Brandell, 1970). The muscle is also active during shoulder horizontal abduction with simultaneous activity of lower trapezius in order to stabilize the scapula (Williams 1949; Brandell, 1970; Arwert et al., 1997). The infraspinatus and the posterior deltoid during external rotation of the shoulder are supported by the middle trapezius, which is stabilizing the scapula so that they can exert their force efficiently (Kuechle et al., 2000). The role of the muscle in abduction or adduction is conflicting (Kronberg et al., 1990b).

Problems in posterior trapezius muscle: Weakness of the posterior deltoid causes weakness in shoulder extension and horizontal abduction. Short posterior deltoid decreases shoulder flexion and horizontal adduction range of motion.

Teres major muscle

Origin: Dorsal surface of inferior angle of scapula.

Insertion: Medial lip of the intertubercular groove of the humerus.

Innervation: Lower subscapular nerve (C6, 7).

Blood Supply: Subscapular and circumflex scapular arteries.

Action: The primary actions of the teres major are adduction, extension and internal rotation of the arm (Kuechle et al., 2000). It acts with rhomboids, primary stabilizator of the scapula, during shoulder adduction and extension.

Problems in posterior trapezius muscle: Weakness in the teres major causes weakness in shoulder adduction, extension, and internal rotation. Short teres major could cause restricted movement in scapulothoracic joint positioning the scapula into abduction and upward rotation.

The arm rotators

Detailed information regarding external rotators (the infraspinatus, teres minor, posterior deltoid, and supraspinatus) and internal rotators (the subscapularis, anterior deltoid, teres major) of the glenohumeral joint has been already given above. Rest of the internal rotators, pectoralis major and latissimus dorsi muscles, will be discussed below in section for *axiohumeral muscles.*

Axiohumeral muscles

The pectoralis major and latissimus dorsi muscles are the axiohumeral muscles based on their attachments on the thorax and the humerus (Fig. 11.41).

Pectoralis major muscle

Origin: Clavicular head: Anterior surface of medial half of the clavicle;

Sternocostal head: Anterior surface of the sternum, superior six costal cartilages, and the aponeurosis of the external oblique muscle.

Insertion: Lateral lip of intertubercular groove of the humerus.

Innervation: Lateral and medial pectoral nerves; clavicular head (C5–6), sternocostal head (C7–T1).

Blood Supply: Pectoral branch of the thoracoacromial trunk.

Action: The primary actions of the pectoralis major are internal rotation, horizontal adduction, and depression of the shoulder (Kuechle et al., 2000). It has great contribution to shoulder internal rotation together with subscapularis muscle and to shoulder depression with latissimus dorsi muscle (Perry et al., 1996; Gagnon et al., 2003). The clavicular head flexes the humerus when it acts alone. The recruitment order of the shoulder flexor muscles during arm raise has been found as first the anterior deltoid, second the clavicular head of the pectoralis major (Jackson et al., 1977). The sternocostal head extends the humerus when it acts alone (Inman et al., 1996).

Problems in pectoralis major muscle: Weakness in the pectoralis major causes weakness in internal rotation, horizontal adduction, and depression of the shoulder. Isolated weakness in sternal head of the pectoralis major cuses decreased strength in shoulder extension from the flexed position.

Latissimus dorsi muscle

Origin: Spinous processes of the inferior 6 thoracic vertebrae, thoracolumbar fascia, to the outer lip of the

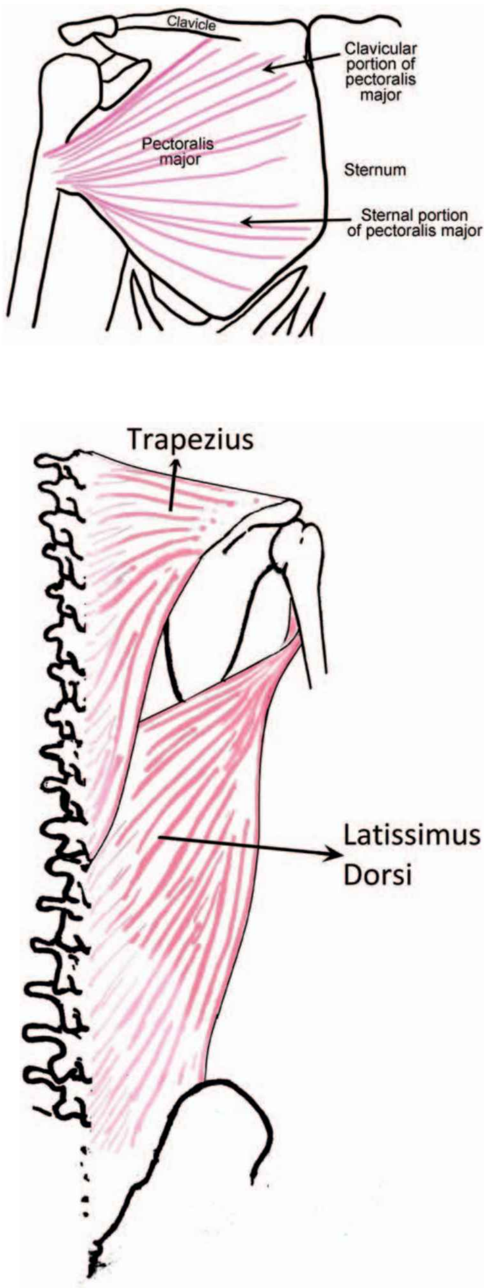
Clavicle
Clavicular portion of pectoralis major
Pectoralis major
Sternum
Sternal portion of pectoralis major
Trapezius
Latissimus Dorsi

FIGURE 11.41 The Pectoralis major and latissimus Dorsi.

posterior aspect of the iliac crest, and inferior 3 or 4 ribs.

Insertion: Floor of the intertubercular groove of the humerus. The muscle may also attach to the lateral aspect of the scapula's inferior angle.

Innervation: Thoracodorsal nerve (C6–8).

Blood Supply: Thoracodorsal artery

Action: The actions of the latissimus dorsi are extension, adduction, internal rotation, and depression of the shoulder (Paton and Brown, 1995; Perry et al., 1996; Gagnon et al., 2003). Working with other humeral depressors, rotator cuff muscles and teres major muscle, it has a role in active control of superior directed translation forces and contributes dynamic stability of the shoulder joint (Kadaba et al., 1992). The latissimus dorsi together with the pectoralis major help stabilize the shoulder joint with their role in depression against superior directed reaction forces during weight-bearing activities such as body lifting with pushing down with the hands during transfer activities of wheelchair users. The muscle also raises the body toward arms during climbing.

Problems in latissimus dorsi muscle: Weakness in the latissimus dorsi causes weakness in shoulder extension, adduction, internal rotation, and depression and contributes instability of the shoulder joint. The ability to raise the body toward arms during climbing is diminished. Tightness of the muscle decreases shoulder flexion, lateral rotation, and abduction range of motion and could cause flexion of the upper thoracic spine leading thoracic kyphosis.

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Chapter 12

Kinesiology of the elbow complex

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Introduction

Elbow joint connects shoulder with hand to provide the upper extremity to move liberally in a harmony. It allows to position our hands to reach an object, stabilizes the upper extremity to perform activities, and assists to throw an object. The wide range of motions of the elbow joint are carried out in a combined fashion during activities (feeding, wearing clothes, personal hygiene, sports, . . .). For all the functions to be performed, the elbow requires a pain-free, mobile, and a stable joint. The stability and the mobility must be in a sense of balance that if one gets dominance the other starts to deteriorate. A sound understanding of elbow kinesiology (anatomy and biomechanics) is essential to recognize the pathomechanics of common disorders of the elbow and treat them accordingly. In this chapter we will discuss the elbow kinesiology in a clinical view and compare with common elbow disorders.

Anatomy

Surface anatomy

The surface anatomic spots of elbow joint are apparent. When the elbow is in extension and supination, the cubital fossa and borders of biceps brachii (BB) muscle in the anterior view, the brachioradialis (BR) muscle in the lateral side, and the medial epicondyle and flexor-pronator muscle group in the medial side, are easily observed (Fig. 12.1). The olecranon, the medial and lateral epicondyles are in an inverted triangular shape when the elbow is in 90 degrees of flexion (Morrey, 2009; Malagelada et al., 2015; Clockaerts et al., 2012) (Fig. 12.2).

Osteology

Humerus

The humerus shaft is round in cross section proximally but flattens and broadens distally to form medial epicondyle and trochlea medially, lateral epicondyle and capitellum laterally (Fig. 12.3).

Medial epicondyle is the origin for medial collateral ligament (MCL) and flexor-pronator muscle group. The lateral epicondyle is the origin for lateral collateral ligament (LCL) and extensor muscle group. The medial epicondyle is more prominent than the lateral epicondyle and bears a posterior groove for the ulnar nerve. The trochlea is the articular surface resembling a spool and articulates with trochlear notch of ulna. The coronoid fossa is located just proximal to anterior side of the trochlea to meet coronoid process during flexion. The capitellum is like a convex hemisphere covering only the anterior part of lateral side of distal humerus which articulates with the concave surface of the radial head. The small radial fossa is located just proximal to anterior side of capitellum. On the posterior side of humerus, there is the deep olecranon fossa which meets olecranon during extension. The condyles of the humerus show a 30 degrees anterior translation to humerus shaft, a 6–8 degrees valgus tilt and a 5 degrees internal rotation in relation to the epicondylar line (Fig. 12.4) (Morrey, 2009; Malagelada et al., 2015; Clockaerts et al., 2012; ten Brinke et al., 2016; Bryce and Armstrong, 2008; Prasad et al., 2003).

In the coronal plane the medial flare of the trochlea extends more distally than the lateral flare which results in a lateral deviation of the ulna with respect to the humerus (Fig. 12.5). This angle between the longitudinal axis of ulna and humerus is called carrying angle and

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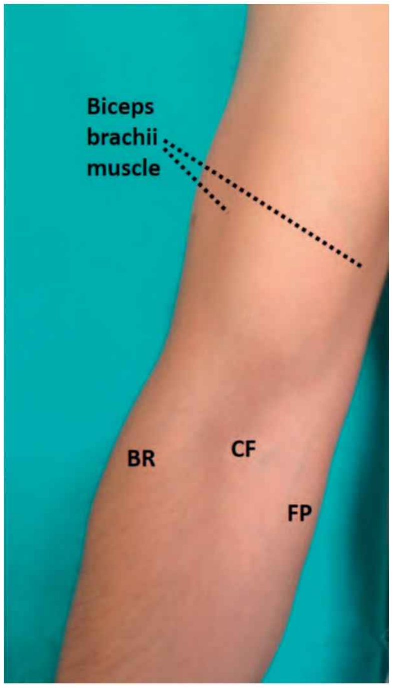

FIGURE 12.1 Surface anatomy (anterior, right elbow extended); BR: brachioradialis, CF: cubital fossa, FP: flexor-pronator muscle group.

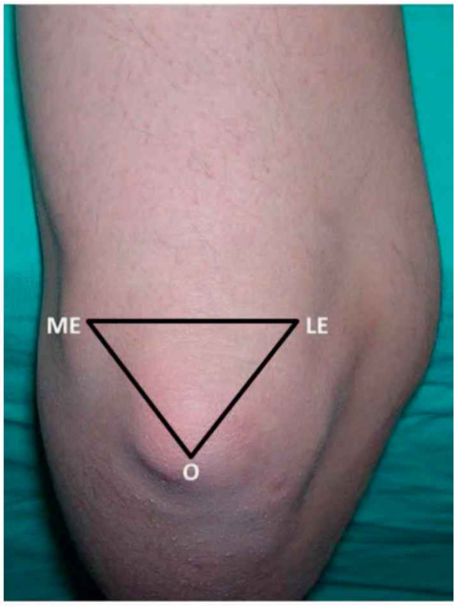

FIGURE 12.2 Surface anatomy, inverted triangle image (posterior, right elbow 90 degrees flexed); ME: medial epicondyle, LE: lateral epicondyle, O: olecranon.

measured when the elbow is in extension and supination (Morrey, 2009; Paraskevas et al., 2004). It is reported to average 11–14 degrees in males and 13–16 degrees in females.

Ulna

The proximal part of ulna (Fig. 12.6) involves olecranon, trochlear notch, coronoid process, radial notch, and supinator crest as important landmarks. Olecranon is easily palpable posteriorly and is the insertion site for triceps tendon. The olecranon is continuous distally with the posterior border of the ulna as the ulnar crest. The trochlear notch is the articular surface of ulna with trochlea of humerus. The coronoid process is an important structure for stability and its base is the insertion site for brachialis muscles anteriorly and medial collateral ligament medially.

The radial notch is an articular depression just distal and radial to the coronoid process and articulates with the radial head in the proximal radioulnar joint (PRUJ). Just distal and posterior to radial notch is the supinator crest, which serves as an attachment site for a portion of LCL. The trochlear notch is in 30 degrees of posterior translation to ulna shaft, which corresponds to 30 degrees of anterior translation of trochlea (Fig. 12.7). This orientation increases the flexion arc and the stability of the elbow joint.

Radius

The proximal part of radius (Fig. 12.8) involves radial head, radial neck, and radial tuberosity as important landmarks. The radial head resembles a disc. It comprises a fovea on superior surface and articulates with convex capitellum to allow flexion-extension motion. The convex circumference of the radial head articulates with the radial notch of ulna to allow pronation-supination motion. Radial head narrows distally to form the radial neck. The radial tuberosity is located on the anteromedial side and just distal to radial neck and serves as the insertion site for biceps brachii tendon. The radial neck has a 10–15 degrees of lateral angulation on coronal plane with the axis of radial shaft.

Arthrology

Articulations

The elbow consists of articulations of humerus, ulna, and radius in three joints; the humeroulnar joint (HUJ), the humeroradial joint (HRJ), and PRUJ (Figs. 12.3 and 12.8).

Articular capsule

The articular capsule encloses all three joints of the elbow, but the epicondyles are outside the capsule. It is a thin structure but reinforced by collateral ligaments (Morrey, 2009; Malagelada et al., 2015; Clockaerts et al., 2012). The capacity of the elbow joint is about 25 mL. The maximum capacity is observed to occur with the

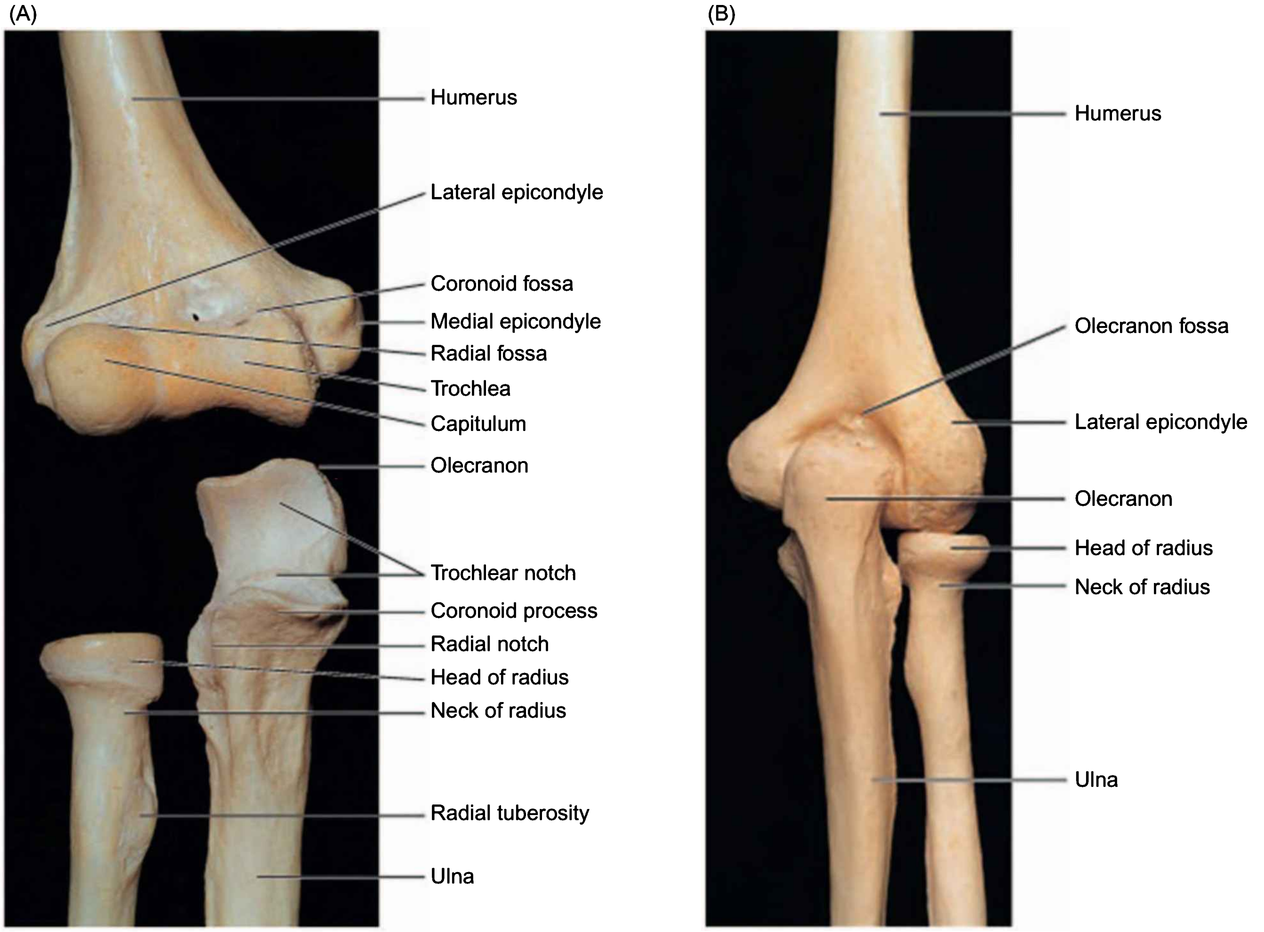

FIGURE 12.3 Important osseous landmarks of distal humerus (A) anterior, (B) posterior.

elbow at about 80 degrees of flexion which explains the 80–90 degrees flexion posture in elbow joint effusions (O'Driscoll et al., 1990).

Medial collateral ligament

MCL consists of anterior, posterior, and transverse bundles (Morrey, 2009; Clockaerts et al., 2012; Bryce and Armstrong, 2008; Prasad et al., 2003; Amis, 2012; An et al., 2009) (Fig. 12.9). Anterior bundle of MCL (AMCL) arises from the anteroinferior part of medial epicondyle and inserts on the anteromedial part of coronoid process. Multiple studies have demonstrated that the anterior bundle is the primary constraint for valgus and posteromedial stability (Morrey and An, 1983; Hotchkiss and Weiland, 1987; Morrey et al., 1991; Floris et al., 1998; Schwab et al., 1980; Sojbjerg et al., 1987). The posterior bundle of MCL (PMCL) arises from medial epicondyle and inserts on the medial side of olecranon. It is an important restraint to valgus stresses during high flexion degrees (more than 120 degrees) and is also important for posteromedial rotatory instability (Floris et al., 1998; Callaway et al., 1997). AMCL has three defined segments; the anterior, the middle, and the posterior (Regan et al., 1991; Fuss, 1991).

The anterior segment is tight in extension, the middle segment is tight in midrange of flexion, and the posterior segment is tight with the PMCL in high flexion degrees. The transverse bundle arises from olecranon and attaches to coronoid process and has no significant effect on elbow stability.

Lateral collateral ligament complex

Lateral collateral ligament (LCL) complex consists of lateral ulnar collateral ligament (LUCL), radial collateral ligament (RCL), and annular ligament (AL). LUCL arises from lateral epicondyle and attaches to supinator crest on ulna. RCL arises from lateral epicondyle and fans out to blend with the AL to stabilize radial head (Fig. 12.10). AL arises from anterior margin of radial notch on ulna and encircles radial head towards the

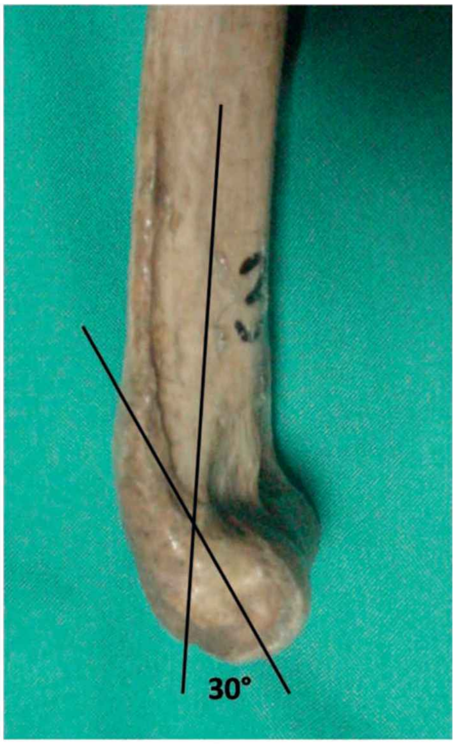

FIGURE 12.4 30 degrees anterior translation of the condyles from the humerus shaft.

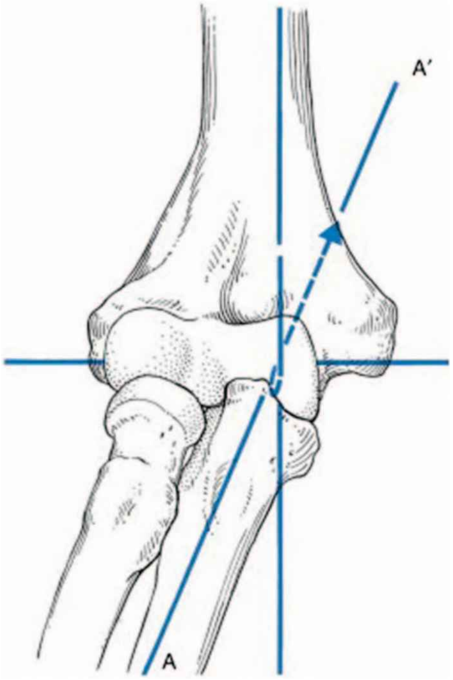

FIGURE 12.5 Carrying angle of the elbow.

attachment site on posterior margin of radial notch. LCL complex is important for posterolateral and varus stability of the elbow.

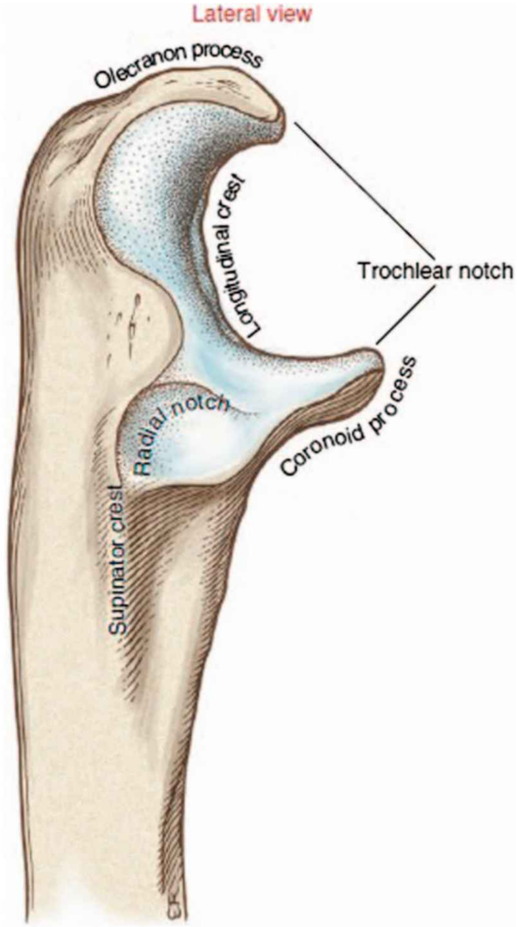

FIGURE 12.6 Important osseous landmarks and articular surfaces of proximal ulna.

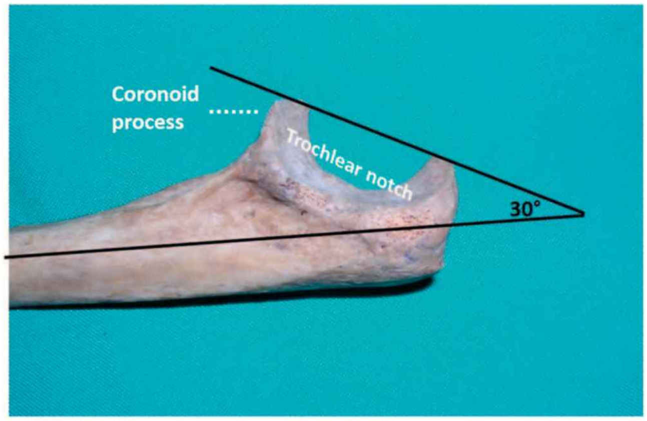

FIGURE 12.7 30 degrees posterior translation of the trochlear notch from the ulna shaft.

The forearm and interosseous membrane

The forearm behaves as a combined unit; PRUJ in the proximal segment, the interosseous membrane (IOM) in the middle segment, and distal radioulnar joint in the distal segment. This unit rotates through the longitudinal axis from radial head to distal radioulnar joint (Oatis, 2013; Neumann, 2017). IOM binds the radius and ulna together through the length of the forearm and its fibers mostly directed from medial surface of radius distally to lateral surface of ulna in an oblique manner (Fig. 12.11). One important exception is the oblique cord, its fibers run distally and perpendicularly from the tuberosity of the ulna to the radius, just distal to its tuberosity.

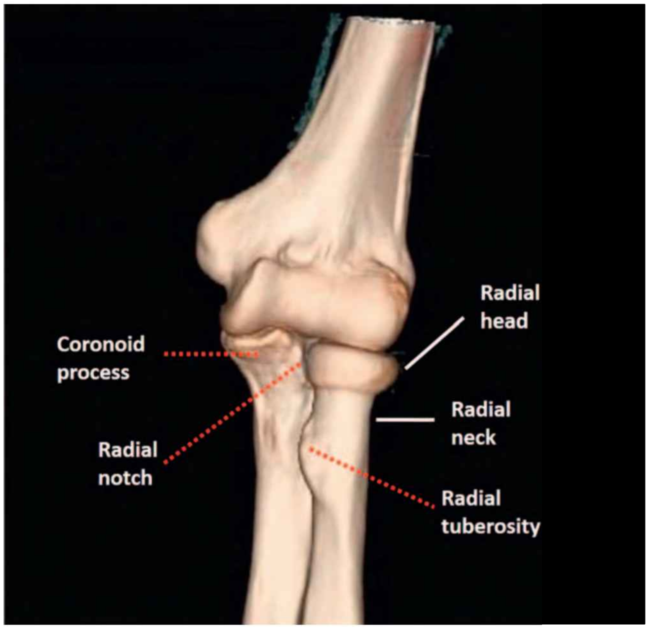

FIGURE 12.8 Important osseous landmarks of proximal radius and articulations of elbow joint.

The IOM has important functions for force transmission and its distally oblique radius-to-ulna fiber orientation is the critical point. The unequal loading of the radius by wrist compression forces (approximately two thirds) is shared with ulna via the IOM fibers direction in the mid-forearm (Shaaban et al., 2006; Fischer et al., 2003; Birkbeck et al., 1997) (Fig. 12.12).

By this mechanism, the elbow is loaded almost equally in HUJ and HRJ. Radius is the distal attachment site for all pronator and supinator muscles, and most elbow flexor muscles. Contraction of these muscles, therefore, pulls the radius proximally against the HRJ. Again, the IOM transfers muscle force from radius to ulna before loading of elbow joint. However, the distraction forces on the wrist joint (e.g., holding a suitcase) slackens IOM; but the oblique cord, the AL, and the muscles (brachioradialis) support radius for the loads (Fig. 12.13) (Oatis, 2013; Neumann, 2017).

Kinematics

The elbow joint has a wide range of motion potential including flexion-extension, pronation-supination, and varus-valgus. It consists of both hinge (HUJ) and trochoid (HRJ) joints, thus can be described as a trochoginglymus

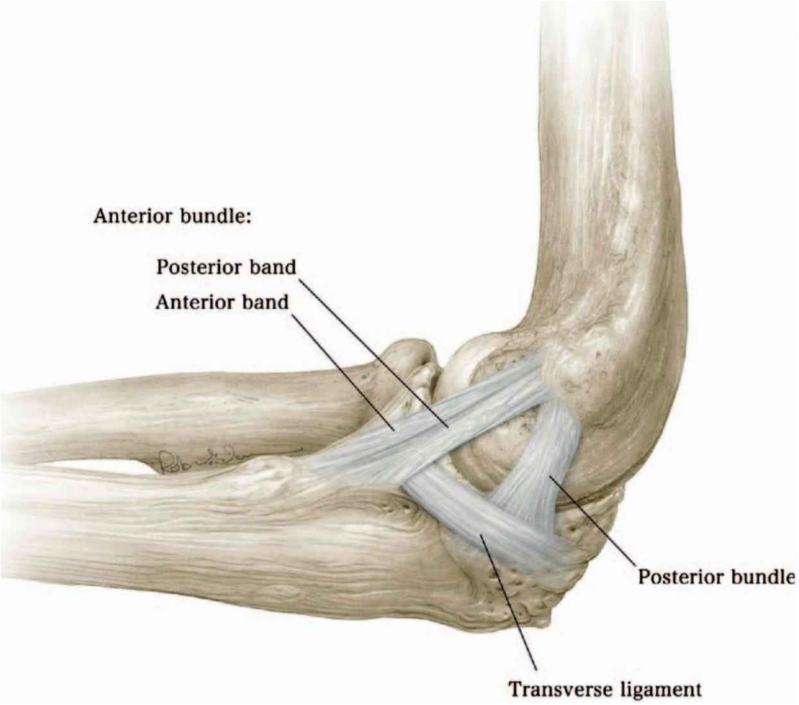

FIGURE 12.9 The bundles of the medial collateral ligament.

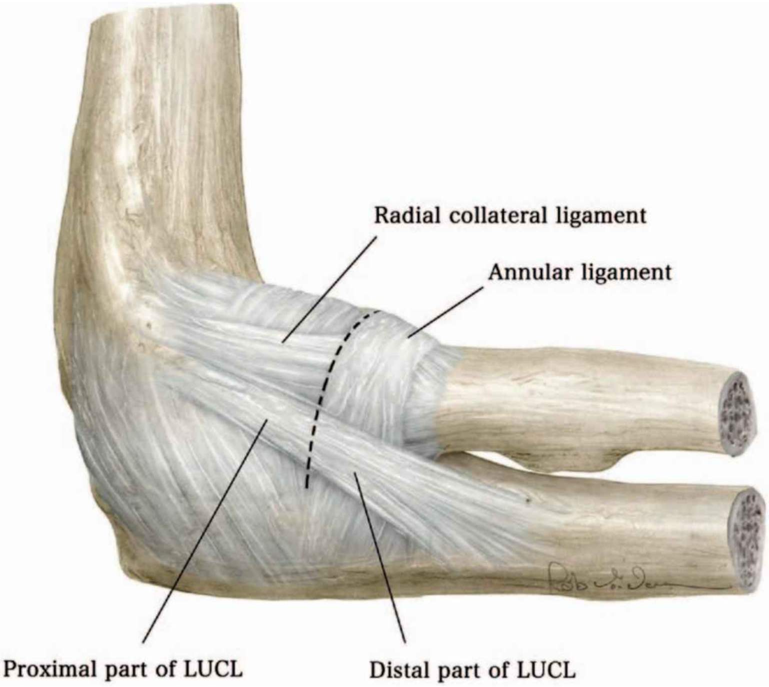

FIGURE 12.10 Lateral collateral ligament complex (Annular ligament fiber orientation is indicated by arrows).

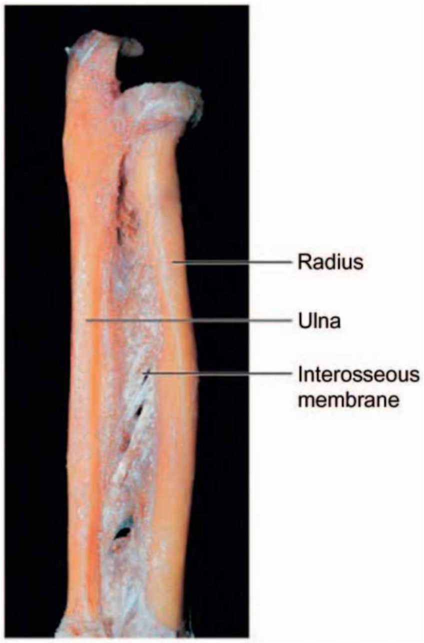

FIGURE 12.11 The interosseous membrane and forearm.

joint. There is a wide variability regarding the "normal" range of motion of the elbow joint in the literature, therefore the contralateral (unaffected) side can be the guide to evaluate the motion restriction (Amis, 2012; An et al., 2009; Oatis, 2013; London, 1981; Lockard, 2006).

HUJ is a highly congruent articulation between trochlea of humerus and trochlear notch of ulna. This is modified hinge type articulation allows flexion and extension, slight abduction and adduction, and a slight amount of axial rotation around ulna (Werner and An, 1994). HRJ is a trochoid articulation between convex capitellum of humerus and concave fovea of radial head. HRJ plays role both in flexion-extension and pronation-supination motions. The PRUJ is a trochoid type joint between radial head and radial notch of proximal ulna. The soft tissues around the PRUJ provides stability and allows forearm pronation and supination.

Flexion and extension

The axis of motion in flexion and extension passes through the center of the arcs formed by the trochlear sulcus and capitellum (London, 1981; Luinge et al., 2007). Although variations exist, the range of motion of elbow is from 0 degrees to 140–150 degrees of flexion (Morrey and An, 2009). Elbow flexion is crucial for daily activities such as feeding, lifting, dressing, and washing hair. Elbow extension is essential for throwing, pushing, and reaching. Several common daily activities can be performed within 30–130 degrees of flexion (Morrey and An, 2009; Morrey et al., 1981)

Pronation and supination

Pronation and supination allow independent rotation of hand with the distal radius gliding about a relatively immobile distal ulna and without an obligatory rotation

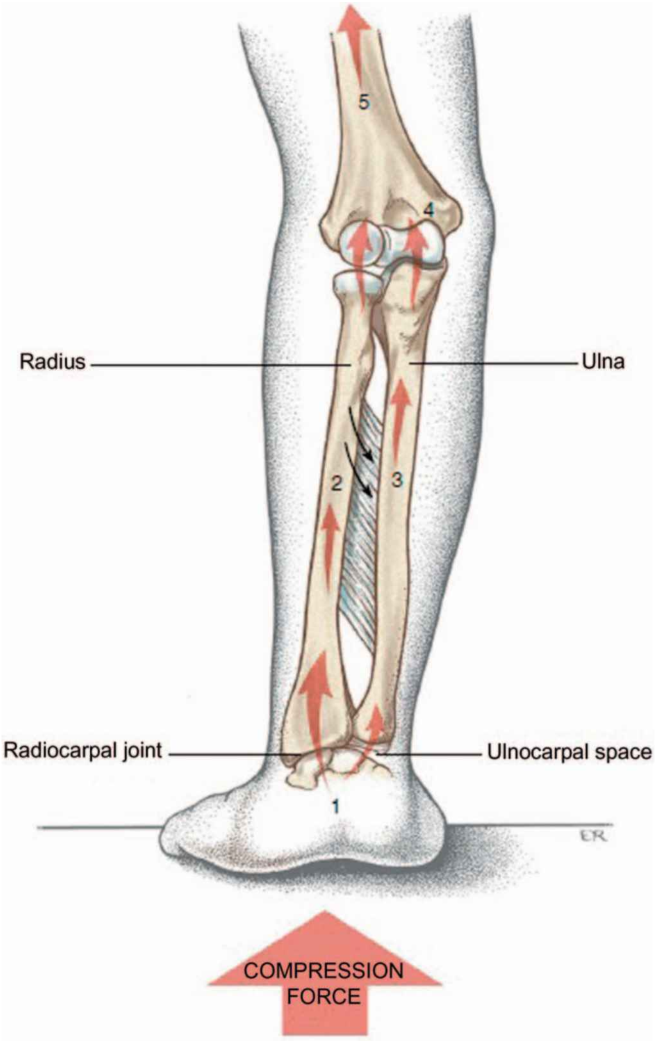

FIGURE 12.12 Compression force through the hand is transmitted primarily through the wrist (1) at the radiocarpal joint to the radius (2). This force stretches the interosseous membrane that transfers a part of the compression force to the ulna (3) and across the elbow at the humeroulnar joint (4). The compression forces that cross the elbow are finally directed toward the shoulder (5).

of ulna or humerus. The ulna slightly abducts during pronation and adducts during supination. Variations has been described but normal forearm rotation averages about 75 degrees pronation and 85 degrees supination (Morrey and An, 2009). Several daily activities are performed in an arc of 50 degrees of pronation and 50 degrees of supination (Morrey and An, 2009). Limitation of more than the last 30 degrees of pronation or supination necessitates obligatory shoulder internal or external rotation which cause difficulties in daily activities (Morrey et al., 1981).

Muscles

The primary muscles of the elbow are defined as those that cross the elbow and attach on the forearm with no attachment across the wrist. These muscles are the biceps brachii, brachialis, brachioradialis, pronator teres, triceps brachii, anconeus, and supinator. The basic concept for the muscles acting on elbow joint is that the muscles attach distally on the radius may supinate or pronate the forearm besides flexor or extensor action (Morrey, 2009; Malagelada et al., 2015; Clockaerts et al., 2012; Bryce and Armstrong, 2008; Prasad et al., 2003; Amis, 2012; An et al., 2009; Oatis, 2013; Neumann, 2017).

The biceps brachii

The biceps brachii muscle (Fig. 12.14) has two origins; long head from supraglenoid tubercle of the scapula and short head from the coracoid process of the scapula. It inserts on the radial tuberosity and it is the primary supinator and important flexor of the forearm. It is innervated by musculocutaneous nerve. Isolated weakness of biceps brachii muscle causes a loss of strength in elbow flexion and supination. However, the remaining elbow flexors and supinators can compensate the actions. (Corner et al., 1990; Rokito et al., 1996). Isolated tightness of the biceps

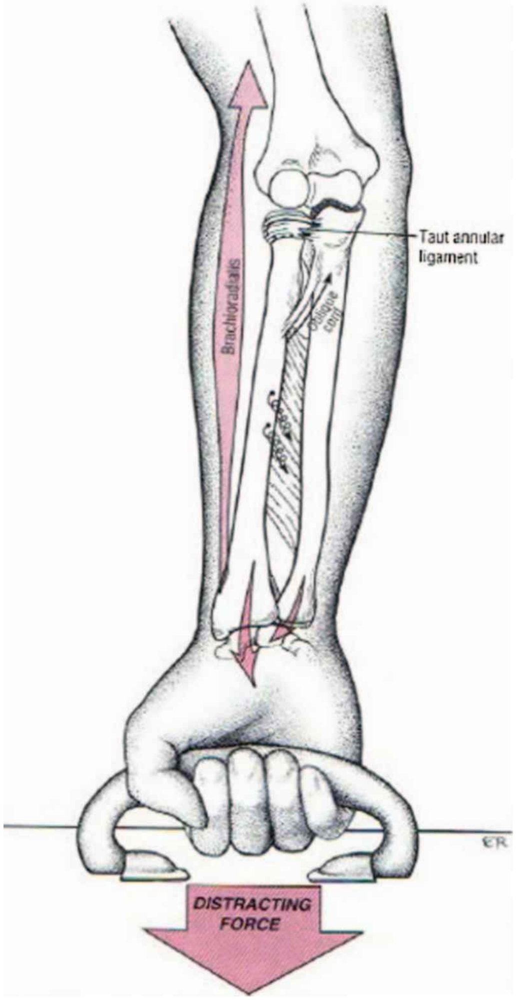

FIGURE 12.13 Distraction force through the hand slackens the interosseous membrane shown by wavy arrows over the membrane. The oblique cord, the annular ligament, and the brachioradialis muscle tighten to assist with the support of the load.

brachii muscle, which is rare to be isolated (e.g., without brachialis muscle and anterior capsule tightness), cause flexion and pronation contracture.

The brachialis

The brachialis muscle is the primary flexor of the elbow joint and inserts on the coronoid process (Fig. 12.15). It is innervated by musculocutaneous nerve.

The brachioradialis

The brachioradialis muscle (Fig. 12.15) attaches proximally on the lateral supracondylar ridge of humerus and inserts distally on the styloid process of radius. It is an important elbow flexor and innervated by radial nerve.

The pronator teres

The pronator teres is located together with flexor-pronator muscle group originating from medial epicondyle. It is primary function is forearm pronation and it also assists for elbow flexion. It is innervated by median nerve.

The triceps brachii

The triceps brachii muscle is the primary extensor of the elbow joint and the anconeus muscle assists for extension of the elbow joint (Fig. 12.16). The triceps brachii muscle has three heads; long head originates from infraglenoid tubercle of the scapula, lateral head and deep located medial head originate from posterior surface of humerus. The common triceps tendon inserts on the olecranon. It is innervated by radial nerve.

The isolated weakness of triceps brachii muscle cannot be elucidated easily in the upright posture, because the gravity works for the extension of the elbow joint. However, overhead extension against gravity would be significantly affected. Pushing a heavy door or rising up from a chair using the upper extremity are classical examples for functional limitations of triceps weakness. Patients without active control of triceps brachii muscle can lock their elbow in extension for certain actions (e.g., C6 tetraplegia patients sliding transfer to and from wheelchairs). However, it was reported that even a 25 degrees of elbow flexion contraction impedes a patient to perform a sliding transfer (Grover et al., 1996). Physicians must be alert for these patients to prevent flexion contractures.

The isolated tightness of triceps brachii muscle limits elbow flexion, which is a serious functional disability. Elbow flexion is required for many daily activities (feeding, washing the face, combing hair etc.).

Tha anconeus muscle

The anconeus muscle is a small triangular muscle attaches to posterior side of lateral epicondyle and inserts on the posterior aspect of ulna proximal region. It is innervated by radial nerve.

The supinator muscle

The supinator muscle lies deep to the extensor muscle group in the proximal forearm and attaches to lateral, anterior and posterior surfaces of the proximal one third of the radius. It is innervated by the posterior interosseous nerve (radial nerve). It supinates the forearm particularly in the extended position of the elbow, when the biceps brachii muscle is inhibited.

Besides the primary muscles of the elbow (no attachment beyond the wrist), the elbow joint is surrounded with

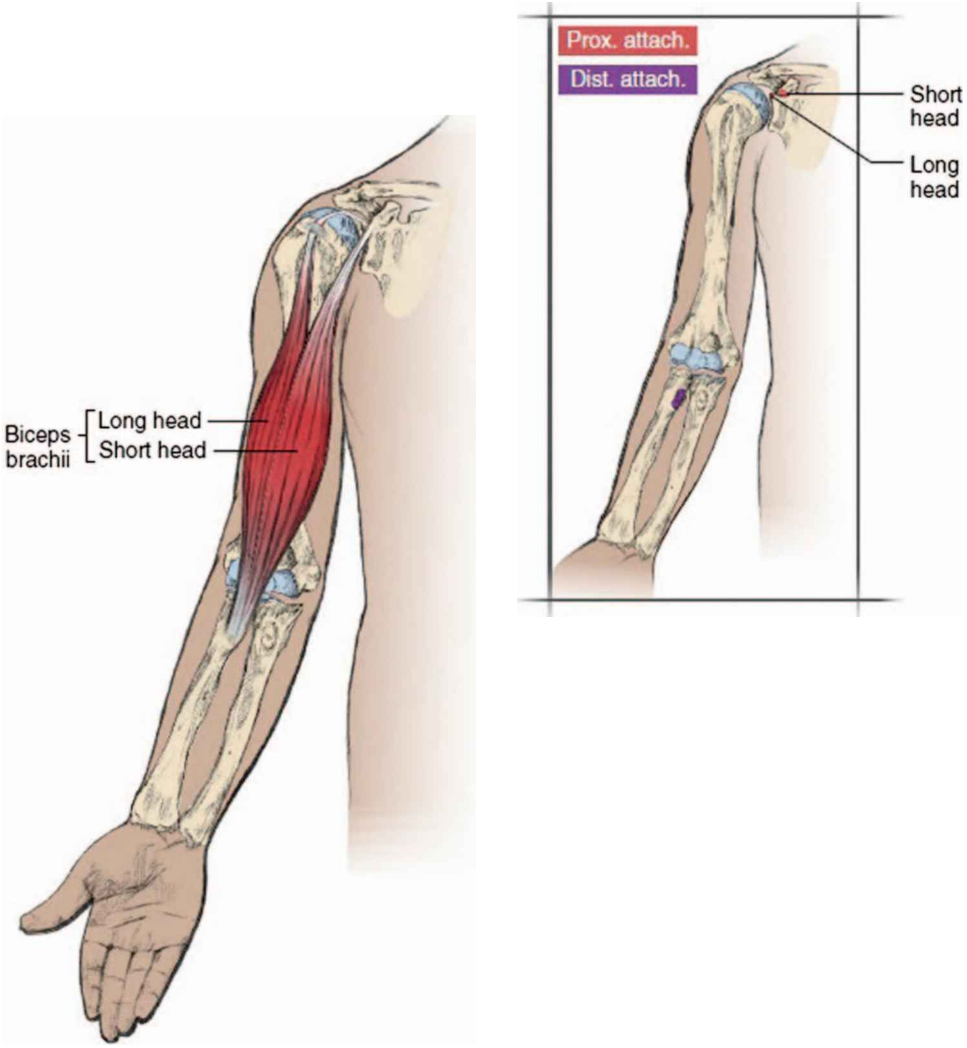

FIGURE 12.14 Biceps brachii muscle.

two muscle groups: Flexor-pronator muscle group medially and extensor-supinator muscle group laterally. These muscles (except the pronator teres, anconeus, and supinator) have actions on wrist and fingers. However, they are also important as dynamic stabilizers of the elbow joint and generally involved in elbow injuries and diseases.

Flexor-Pronator muscle group

Flexor-pronator muscle group originates from medial epicondyle and includes pronator teres, flexor carpi radialis, palmaris longus, flexor digitorum superficialis, and flexor carpi ulnaris. This muscle group serves as a dynamic stabilizer against valgus loadings. (Davidson et al., 1995; Park and Ahmad, 2004) The pronator teres has humeral and ulnar origins, it is a strong pronator of the forearm and a weak flexor of the elbow. The palmaris longus is functionally insignificant but is useful as a tendon or ligament graft donor for reconstructive procedures.

Extensor-Supinator muscle group

Extensor-supinator muscle group originates from lateral epicondyle and includes anconeus, extensor carpi radialis longus (ECRL), extensor carpi radialis brevis (ECRB), extensor digitorum communis, extensor digiti minimi, extensor carpi ulnaris, and supinator muscles. This muscle group serves as a dynamic stabilizer against varus and postreolateral loadings. The mobile wad of Henry includes the BR, the ECRB, and the ECRL, forms the radial-sided contour of the forearm and lateral border of the antecubital fossa (Adams and Steinmann, 2011).

Stability

Stability of the elbow is provided together by static and dynamic constraints (O'Driscoll et al., 2001). Awareness of the function and likelihood of injury of each stabilizing structure is needed for management of elbow trauma (Bryce and

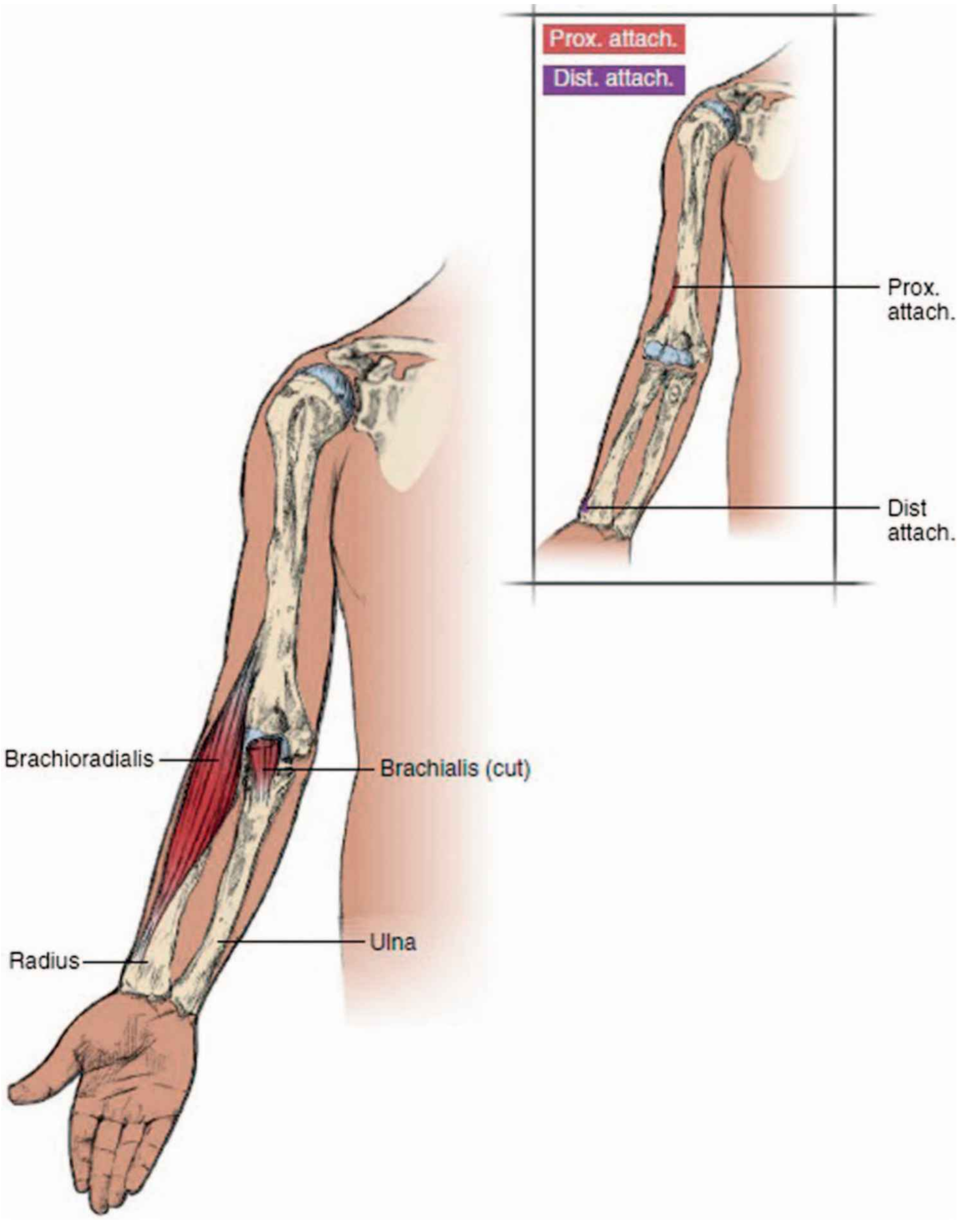

FIGURE 12.15 Brachioradialis muscle and the insertion of brachialis muscle on coronoid process of ulna.

Armstrong, 2008).The three primary static constraints include the HUJ, the anterior bundle of the MCL, and the LCL complex. If these three structures are intact, the elbow is stable. The most important secondary constraint is the radial head, which takes the role of missing primary constraint in its deficiency. Other secondary constraints include the flexor-pronator muscle group, the extensor-supinator muscle group, and the capsule (Morrey, 2009; Kancherla et al., 2014).

The HUJ is the primary osseous stabilizer and responsible for almost 50% of the stability of the elbow joint (Morrey and An, 1983). Osseous stability is enhanced in flexion when the coronoid process locks into the coronoid fossa, and the radial head is contained in the radial fossa (Bryce and Armstrong, 2008). Osseous stability is enhanced in extension when the tip of the olecranon inserts into the olecranon fossa. The coronoid needs special attention because it is the most important bony structure for posterior-anterior stability and also for varus-valgus stability (Beingessner et al., 2007; Hull et al., 2005; Closkey et al., 2000; Schneeberger et al., 2004). Soft tissues that insert to the coronoid include capsule and brachialis anteriorly and AMCL anteromedially. These soft tissues are also important for stability which enhances the role of coronoid for inherent stability of the elbow joint.

The anterior bundle of MCL is the primary constraint for valgus and posteromedial stability (Morrey and An, 1983;

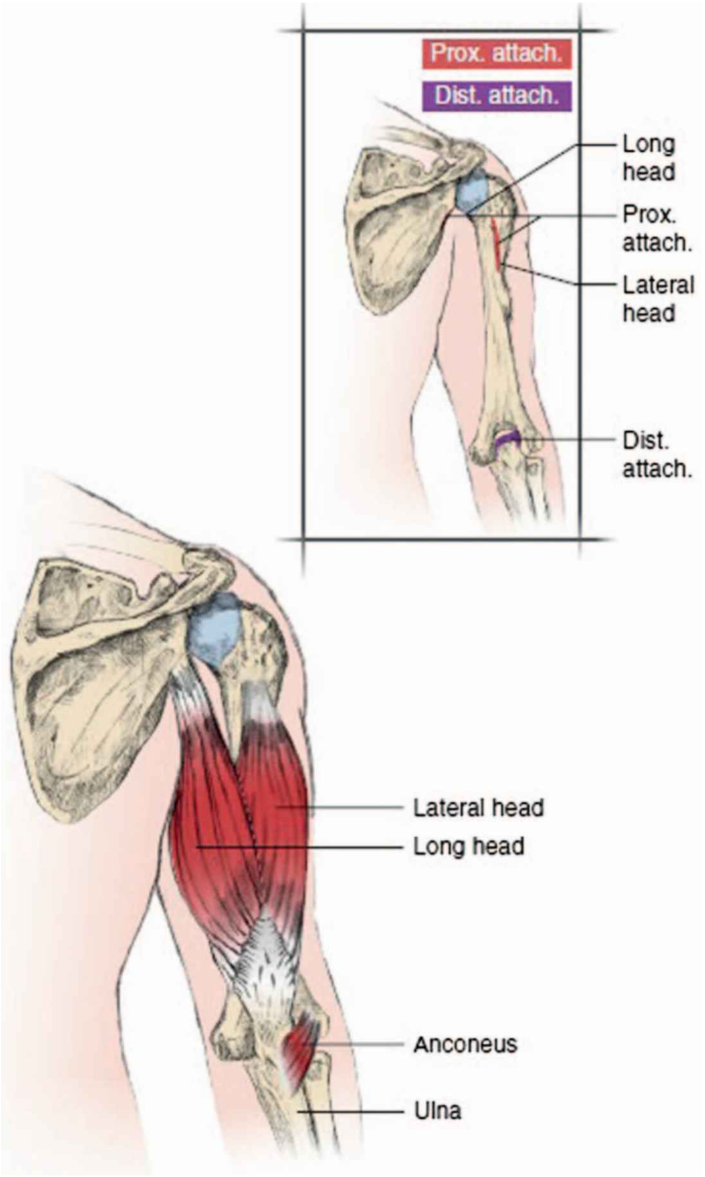

FIGURE 12.16 Triceps brachii muscle.

Hotchkiss and Weiland, 1987; Morrey et al., 1991; Floris et al., 1998; Schwab et al., 1980; Sojbjerg et al., 1987). The LUCL is the primary constraint for varus stress and posterolateral rotatory instability of the elbow (Bryce and Armstrong, 2008; Olsen et al., 1996; Cohen and Hastings, 1997; Morrey and An, 1985). The LUCL and the anterior bundle of MCL originates on the axis of rotation and stays in the same tension during the flexion and extension of elbow joint. The collateral ligaments provide approximately 50% of the varus-valgus stability of the joint, and the articular surfaces provide an additional 50%. But in full extension of the elbow, the anterior capsule takes the role of collateral ligaments and acts as an important varus and valgus stabilizer together with the articular surfaces (Deutch et al., 2003; Morrey and O'Driscoll, 2009).

The radial head is the most important secondary stabilizer of the elbow joint when the primary stabilizers are missing. Firstly, it is an important valgus stabilizer of the elbow secondary to MCL (Morrey and An, 1983; Hotchkiss and Weiland, 1987; Morrey et al., 1991). If the medial collateral ligament is intact, the radial head offers little resistance to valgus stress, but if the medial collateral ligament is deficient, the radial head becomes an important valgus stabilizer. Secondly, it is an important bony stabilizer for anteroposterior osseous stability of the elbow joint secondary to coronoid. If the radial head is intact, the elbow joint remain stable even when the 50%

of coronoid is deficient (An et al., 2009). Last but not least, the radial head also has role for posterolateral rotatory stability secondary to LUCL (Floris et al., 1998; Morrey and O'Driscoll, 2009; Mehta and Bain, 2004; Dunning et al., 2001).

Muscles crossing the elbow are dynamic stabilizers of the joint (O'Driscoll et al., 2001). When a muscle produce motion, the antagonist of it must compress elbow joint to increase stability (King et al., 1993; Ahmed and Mistry, 2015; Safran and Baillargeon, 2005). This concept is valid for both flexion-extension movement and varus-valgus loads. For example, throwing an object can cause a valgus stress that is greater than the failure strength of the MCL. The flexor-pronator muscle group contracts during the throwing motion and provides dynamic stabilization to the medial aspect of the elbow, which protects the MCL from injury (Park and Ahmad, 2004). The extensor-supinator muscle group in the lateral side of elbow resist varus forces and the anconeus deserves specific attention, because it is a major dynamic constraint to varus and posterolateral rotatory instability (Bryce and Armstrong, 2008; Safran and Baillargeon, 2005).

Instability

Instability of the elbow can be the result of a single traumatic event, such as fracture-dislocation or from chronic attritional injury to ligamentous structures as seen in throwing athletes. Patients with elbow instability often do not appreciate "giving way," "clunking," or other more obvious mechanical symptoms, but instead complain that they cannot use their elbows with force in certain positions or cannot perform certain activities.

When the anterior bundle of MCL is injured, valgus stress produces opening on the medial side of the joint, often accompanied by pain. This stress should be applied with the joint flexed a minimum of 20–30 degrees to relax the anterior capsule and to eliminate the osseous constraint of the olecranon process of the ulna being "locked" into the olecranon fossa, as occurs in full extension. The LUCL resists varus forces at the ulnohumeral joint, prevents external rotation of the ulna off the distal humerus, and supports the position of the radial head. Injury to LUCL results in the phenomenon known as posterolateral rotatory instability (PLRI) of the elbow. In this circumstance, the proximal radius and ulna, which maintain their normal relationship at the proximal radioulnar joint, supinate away from the lateral aspect of the distal humerus, hinging on the intact medial collateral ligament. In the subluxated position, the radial head lies posterior to the capitellum and the lateral aspect of the ulnohumeral articulation is widened (Fig. 12.17) (Adams and Steinmann, 2011).

PLRI is demonstrated by using the pivot shift test in which the examiner subjects the elbow to supination, valgus, and compressive stress (O'Driscoll et al., 1991). This maneuver is best performed with the humerus locked in full external rotation. As the elbow is extended from a semiflexed position, posterior subluxation of the radial head can be appreciated and often causes a dimpling in the skin on the lateral aspect of the joint; maximum subluxation usually occurs at about 40 degrees of flexion. Further flexion of the elbow results in a sudden reduction

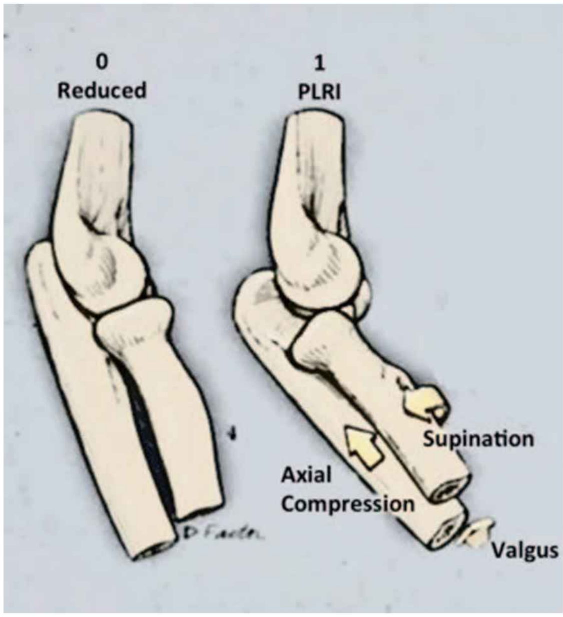

FIGURE 12.17 In posterolateral rotatory instability (PLRI), the radial head subluxates posteriorly and the ulnohumeral articulation is widened. Supination, valgus, and compression applied to elbow joint in slight flexion causes this pattern of subluxation after lateral ulnar collateral ligament injury.

of the radius and ulna onto the humerus. This maneuver may be most easily performed with the patient supine on the exam table with the arm overhead. Examination under anesthesia is generally required to demonstrate this finding. In the awake patient, the chair sign and push-up sign are helpful for PLRI diagnosis (Regan and Lapner, 2006). The chair sign involves having the patient stand up from a chair while pushing with the upper extremities and keeping the forearms in supination and the arms abducted to greater than the shoulder width. The test is considered positive if there is hesitancy to extend the elbow fully as the patient raises his body using exclusively upper extremity force or a dislocation occurs. The push-up sign involves having the patient perform an active floor or wall push-up with the forearms supinated and the arms abducted to greater than the shoulder width. The test is considered positive if the patient shows hesitancy to fully extend the elbow or a dislocation occurs.

Elbow kinesiology in acute traumatic injuries

Elbow simple dislocations

The elbow is the second most commonly dislocated joint, after the shoulder, in adults. In the pediatric age group, it is the most commonly dislocated joint (Tarassoli et al., 2017). Both simple dislocations and fracture-dislocations can be followed with stiffness or instability. Therefore, the issue is to restore articular congruity and stability enough to allow for early range of motion exercises.

Elbow dislocation pathomechanics is well described (O'Driscoll et al., 1992, 2001). The soft tissue injury starts from the lateral side and can extend to medial side of the elbow in advanced stages. The stages correlate with clinical degrees of elbow instability. In stage 1, the lateral ulnar collateral ligament is injured; in stage 2, other lateral ligamentous structures and capsule are injured; in stage 3A, the PMCL is injured; and in stage 3B, the AMCL is injured.

The importance of osseous stabilization of the elbow joint is illustrated by the elbow simple (no fractures) dislocation. Most simple elbow dislocations are relatively stable once reduced, despite prominent soft tissue injury (Eygendaal et al., 2000; Josefsson et al., 1987, 1987). After closed reduction of simple dislocation of the elbow, except the stage 3B, the intact anterior bundle of MCL preserves the joint stability and allows for early range of motion exercises. Here, both the hinge effect of medial structures in pronation and the dynamic stabilizing effects of the muscles crossing the elbow joint play important role for stability. In 3B injuries, the fulcrum effect of medial structures are lost and gross instability of the elbow joint in extension can be observed.

Elbow fracture dislocations

Several bony injuries (coronoid fracture, radial head fracture, capitellum fracture, medial epicondyle avulsion etc.) can accompany to soft tissue injuries of elbow dislocation (Tarassoli et al., 2017). In such cases, the treatment regimen changes and generally surgical repair/reconstruction is performed.

The most typical example of the elbow fracture dislocations, the 'terrible triad', is defined as elbow dislocation with associated radial head and coronoid fractures. As the LCL is inevitably injured in elbow dislocations, all the three important stabilizer structures are reconstructed if possible. The LCL complex must be repaired after radial head fixation or replacement, particularly in complex elbow fracture dislocation injuries.

The coronoid process is the most important osseous structure for stability and commonly fractured during fracture-dislocations of the elbow. The isolated coronoid fractures that involve more than 50% of the coronoid cause gross instability of the elbow. When the radial head is fractured, the instability can occur even with more than 50% of coronoid is preserved. Both anteroposterior and varus-valgus stability is disrupted (Beingessner et al., 2007; Hull et al., 2005; Closkey et al., 2000; Schneeberger et al., 2004). In a coronoid deficient elbow, the posterior directed muscular forces on coronoid cause posterior translation of ulna off the humerus. The instability occurs during both flexion (brachialis and biceps brachii) and extension (triceps) of elbow joint. Therefore, in cases of instability the coronoid fixation is performed if possible.

Radial head fractures must be fixed if possible, but if it is much comminuted that not amenable to reconstruction, then, replacement with a radial head prosthesis is required for proper elbow biomechanics. The precise positioning is important for radial head prosthesis. Van Glabbeek et al. (2004) showed that the lengthening and shortening of the radial neck by 2.5 mm significantly alters the kinematics and contact pressure through the radiocapitellar joint in the medial collateral ligament-deficient elbow. Radial neck lengthening caused a significant decrease in varus-valgus laxity and ulnar rotation, with the ulna tracking in varus and external rotation. Shortening caused a significant increase in varus-valgus laxity and ulnar rotation, with the ulna tracking in valgus and internal rotation.

In summary, for any form of fracture dislocation, an acceptable HUJ stability should be restored for the fundamental stability of the elbow joint by fixing coronoid fractures and radial head fractures if possible. If the radial head fracture is comminuted and not amenable for fixation, it is replaced with radial head prosthesis. The lateral ulnar collateral ligament must be repaired. An articulated external fixator is applied if instability persists for HUJ (Kamineni et al., 2007; McKee et al., 1998; Morrey, 1995; Pugh et al., 2004).

Elbow trauma and its sequela

Distal humerus, proximal ulna, or proximal radius fractures requires anatomic reconstruction of not only the articular surfaces but also the fossae around elbow. Otherwise, even minute amounts of bony malalignments can have a significant influence on the ROM at the elbow following the fracture. Also, elbow trauma may promote adhesions and scarring, which can cause elbow stiffness and compression neuropathies. The three main nerves around elbow (ulnar, median, and radial) pass in a close relationship to the bony structures and therefore, they are prone to injuries during elbow trauma or surgical procedures. The nerves are susceptible to injuries especially in association with pediatric supracondylar fractures.

Alteration of the carrying angle may be caused by malunion of fractures around the elbow or a growth disturbance resulting from physeal injury, however, it is not uncommon to find increased valgus due to adaptive changes in throwing athletes (King et al., 1969). Cubitus varus is caused by a reversal of the normal valgus carrying angle and, when significant, is termed a gunstock deformity. Cubitus valgus is used to describe an exaggeration of the normal valgus carrying angle. This deformity may cause a traction neuropathy of the ulnar nerve over years termed as tardy ulnar nerve palsy.

Stiffness

The inability to actively flex or extend the elbow joint, or the inability to actively pronate or supinate the forearm, despite full passive ROM, must be distinguished from elbow stiffness (Altman, 2011). The former generally occurs by neurogenic problems (brachial plexus injury, brain injury, poliomyelitis, tetraplegia, . . .) and necessitates an entirely different clinical approach. In stiff elbow, the passive ROM is limited as well, and generally no neurogenic problem is encountered. Elbow flexion limitation may occur after trauma due to intracapsular hemorrhages, or posttraumatic ectopic bone formation. Elbow extension limitation may occur after long term casting, elbow joint inflammation, elbow flexor muscle spasticity, anterior capsular scarring, or scarring of the skin over the anterior elbow.

The elbow joint has a great tendency for capsular contracture following elbow trauma, surgery, or a short period of immobilization. Trauma, especially fracture-dislocation of the elbow joint is the most common cause for elbow stiffness. The brachialis muscle that crosses the anterior capsule tears with dislocation, developing scar tissue or ectopic bone when healing, often associated with contracture of the capsule (Loomis, 1944; Nowicki and Shall, 1992; Hildebrand et al., 2005; Morrey, 2005). Moreover, arthritis, burns, head trauma, and congenital abnormalities may lead to elbow stiffness, as well. In adults, nontraumatic elbow contractures are usually caused by osteoarthritis.

The elbow stiffness may be caused by extrinsic or intrinsic factors:

Extrinsic: The pathology is outside the joint (ligaments, muscles, capsule, heterotopic ossification). The contracted elements generally respond well to therapy (gentle stretching, use of orthoses). The resection or lengthening of contracted structures may be necessary.

Intrinsic: The pathology is inside the joint (intraarticular adhesions, articular incongruence (malunion), osteophytes, loose bodies). Articular anatomy must be restored surgically. Therapy would not be effective if the articular anatomy was not restored.

Mixed: These are more frequent. The pathology is both inside and outside the joint. Almost all intrinsic contractures have an extrinsic component already settled. The adaptive shortening of the capsule, muscles, and ligaments take place.

Elbow contractures are classified as flexion contractures, extension contractures, pronation contractures, and supination contractures. A flexion contracture describes an elbow that lacks extension, which can be compensated with trunk flexion and shoulder motion. An extension contracture describes an elbow that lacks flexion. It is hard to compensate elbow flexion lack with wrist and neck flexion and extension contracture of elbow is more functionally limiting. A pronation contracture describes a forearm that lacks supination. It is seen more commonly than a supination contracture, which describes a forearm that lacks pronation. Pronation is required for many activities of daily living, such as keyboard use, but a deficit can be compensated for with shoulder abduction. Supination is needed for tasks such as extending the palm to receive change or holding a tray, but compensation for the lack of supination is very difficult.

The critical point is that one must distinguish the cause of motion restriction. Any bony block requiring surgical correction must be analyzed carefully to avoid waste of time with stretching exercises only. During physical examination, it is important to recognize the end-point feel of the passive ROM. Any bony block is felt as a hard-stop of motion, but the soft tissue contracture has a rather soft-stop feeling of motion. In any suspicious situations, a three dimensional computerized tomography is a good option to clarify the bony structures.

Elbow injuries in the athlete

Overhead throwing activities are related to several overuse injuries. The throwing athlete coils his body sequentially starting from his lower extremities and making headway through the trunk. Next, the energy is transferred to externally rotated shoulder and augmented by the muscles around the shoulder. Finally, with the internal rotation of the upper arm the energy explodes on the elbow as valgus and extension forces (Kancherla et al, 2014; Maloney et al, 1999; Elliott, 2006).

Slocum (Slocum, 1968) first categorized elbow injuries in athletes into three patterns: medial tension overload injury, lateral compression overload injury, and extension overload injury. The combination of valgus forces with rapid elbow extension produces tensile stress along the medial side (MCL, flexor-pronator muscles, medial epicondyle, and ulnar nerve), compression stress on the lateral side (radial head and capitellum), and shear stress in the posterior compartment (posteromedial tip of the olecranon and olecranon fossa) (Fig. 12.18). This phenomenon has been termed "valgus-extension overload syndrome" and forms the basic pathophysiologic model behind the most common elbow injuries in the throwing athlete (Wilson et al., 1983; Fleisig et al., 1995; Andrews and Whiteside, 1993).

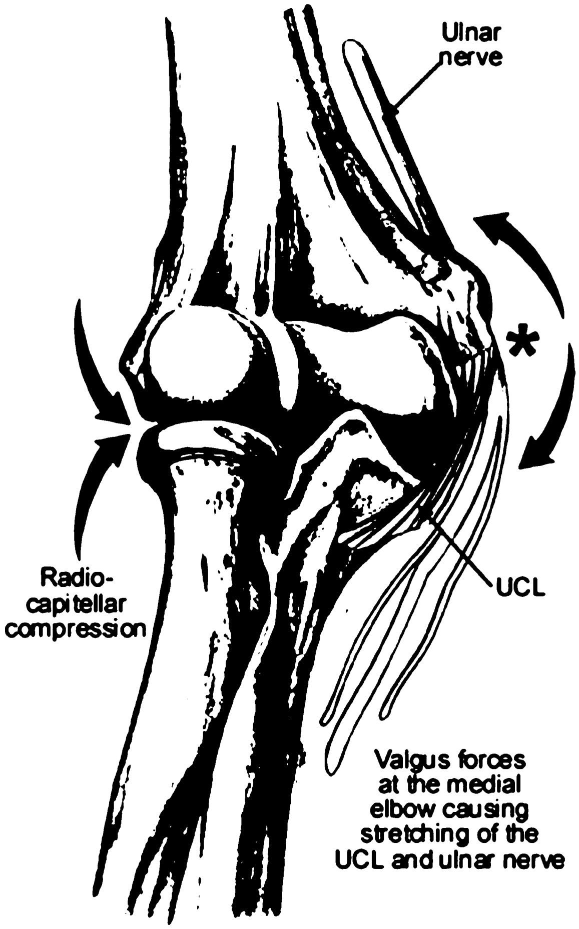
Ulnar nerve
*
UCL
Radio-capitellar compression
Valgus forces at the medial elbow causing stretching of the UCL and ulnar nerve

FIGURE 12.18 Biomechanical forces within the elbow joint during throwing.

Medial elbow pain

Repetitive valgus stress, flexor and pronator activity can lead to medial elbow symptoms arising from any combination of four distinct but etiologically interrelated pathological conditions: flexor-pronator muscle injuries (medial epicondylitis), MCL injury, and ulnar neuropathy.

Flexor-pronator muscle injuries and medial epicondylitis

The tendinous origins of the flexor-pronator muscles are predisposed to injury because of their dynamic function against valgus stress (Regan et al., 1991). The injury can occur as tendinitis, medial epicondylitis, or acute tears (Cain et al., 2003). Pain produced by palpation just distal to the tip of the medial epicondyle that is exacerbated by resisted wrist flexion and pronation is indicative of tendinitis and/or medial epicondylitis. The interface between the pronator teres and flexor carpi radialis origin is the most common site of pathology, but pathological tissue can also be seen at the flexor carpi ulnaris and palmaris longus origins as well as on the undersurface of the flexor digitorum superficialis (Nirschl, 1988). These patients have pain with resisted wrist flexion and forearm pronation, in addition to grip weakness relative to the contralateral extremity (Pienimaki et al., 2011).

Ulnar neuropathy

The ulnar nerve has a tethered location posterior to the medial epicondyle while traveling through the fibroosseous cubital tunnel. With elbow flexion, the pressure inside the cubital tunnel increases 7- to 20-fold, aiding compression neuropathy of the ulnar nerve (Posner, 1998). Moreover, the repetitive throwing stresses cause medial-sided overuse injuries, which in turn causes traction injuries of the ulnar nerve (Aoki et al., 2005; Toby and Hanesworth, 1998; Conway et al., 1992; Glousman, 1990). Traction neuropathy due to valgus stress, or compression neuropathy due to adhesions, osteophytes of the medial epicondyle, flexor muscle hypertrophy are possible causes for ulnar neuropathy in the throwing athlete. The athletes commonly complain of paresthesia in the small and ring fingers during or after the throwing motion, and tenderness or a positive Tinel's sign is often present at the site of ulnar neuropathy (Cain et al., 2003).

Medial collateral ligament injury

MCL injuries has been described extensively in athletes (Andrews and Whiteside, 1993; Conway et al., 1992; Indelicato et al., 1979; Jobe et al., 1986). Repetitive stresses can lead to microtears in MCL due to valgus-extension forces. The microtears cause attenuation of MCL with medial sided elbow pain and possible future ligament rupture with instability. Attenuation of MCL leads to abnormal valgus movement of the elbow joint affecting the biomechanics of the elbow. Moreover, Pomianowski et al. (2001) demonstrated that forearm pronation increases valgus/varus laxity. Therefore, the pronation position of forearm in throwing kinematics increases the risk of medial collateral ligament injury due to chronic valgus overload.

In the presence of a disrupted MCL, the lateral and posterior sides of the elbow are affected, as well. The compression forces over the radiocapitellar joint increases and extensor muscles starts to contract asynchronously. Glousman et al. (1992) compared electromyographic data obtained from a group of baseball pitchers who were medial ulnar collateral insufficient, and compared these data with a group of healthy pitchers and demonstrated that the extensor carpi radialis brevis and longus muscles showed greater activity in the injured pitchers. This increased activity may not only contribute to further joint injury through its asynchronous action but also predispose athletes to lateral epicondylitis. Moreover, MCL insufficiency alters contact area and pressure between the posteromedial trochlea and olecranon, and causes bony impingement at the posteromedial trochlea (Ahmad et al., 2004). Such impingement can lead to chondral lesion and eventually development of posteromedial osteophytes (Andrews, 1985).

Lateral elbow pain

There are two different pathomechanics for lateral elbow overuse injuries (Field and Savoie, 1998). In a throwing athlete, repetitive valgus stress in the presence of an injured or incompetent medial ulnar collateral ligament results in abnormal compression of the articular surfaces of the radiocapitellar joint (Morrey et al., 1991). Arthosis, fragmentation and loose body formation can result from this radiocapitellar joint overload. The second mechanism is related with lateral epicondylitis which is caused by intrinsic muscular micro tears. Micro tears occur within the tendon as a consequence of overload contractions as the probable inciting factor to tendon degeneration. However, one must consider that both pathologies may co-exist. Finally, radial tunnel syndrome due to compression of posterior interosseous nerve can occur and coexist with lateral epicondylitis.

Osteochondritis dissecans of capitellum

Radiocapitellar compression can lead to osteochondritis dissecans (OCD) of capitellum, also known as Panner disease (Ahmad et al., 2011). It occurs most frequently in young male throwing athletes and female gymnasts. OCD is a noninflammatory degeneration of subchondral bone of the capitellum that has been reported to be due to ischemia, trauma, and genetic factors (Schickendantz, 2002).

Lateral epicondylitis and radial tunnel syndrome

The degenerative process known as lateral epicondylitis (tennis elbow) primarily involves the origin of the extensor carpi radialis brevis. Although originally described as an inflammatory process, the current consensus is that lateral epicondylitis is initiated as a micro tear following repetitive microtraumatic injury (Adams and Steinmann, 2011; Field and Savoie, 1998; Inagaki, 2013). Micro tear try to heal with granulation tissue and fibrosis, nevertheless, the repetitive injury continues, and finally the tendon undergoes degeneration failure over time (Regan et al., 1992).

Lateral epicondylitis occur during activities that require repetitive supination and pronation of the forearm with the elbow in near full extension. In these cases, pain on palpation is located just distal or adjacent to the tip of the lateral epicondyle, and symptoms are exacerbated by resisted wrist extension, particularly when the elbow is fully extended, thereby placing the muscle on maximum stretch.

The radial nerve passes through the anterolateral aspect of the elbow joint, then divides into the posterior interosseous nerve (PIN), a motor nerve which innervates the extensor-supinator muscles of the forearm, and the superficial sensory radial nerve. The PIN enters the radial tunnel at the level of the HRJ. The radial tunnel borders extends proximally form the medial sides of brachialis muscle and biceps brachii tendon and lateral side of mobile wad, distally to supinator muscle distal border. The floor of the tunnel is formed by the anterior capsule of the elbow and the deep head of the supinator. Entrapment of PIN (radial tunnel syndrome) can occur due to repetitive pronation-supination activities (e.g., tennis, swimming) and can coexist with lateral epicondylitis. The pain is localized over the lateral elbow and proximal forearm and is usually described as dull, aching, and exertional. The tenderness is located slightly more distal than the lateral epicondyle over the extensor muscle mass but to localize an exact level of compression based solely on the physical examination may be difficult. Although not being always confident, diagnosis can be confirmed by electromyographic investigation (Roles and Maudsley, 1972).

Posterior elbow pain

Valgus extension overload syndrome can occur during overhead throwing sports. Posteromedial osteophyte formation can lead to posterior impingement, also repetitive trauma can cause to olecranon stress fracture.

Posterior olecranon impingement

Overuse, improper throwing mechanics, or poorly conditioned muscles can lead to triceps strain with subsequent inflammation (Maloney et al., 1999). A commonly seen pathologic entity resulting from chronic valgus extension overload is the development of posteromedial osteophytes, resulting in impingement within the olecranon fossa (Kancherla et al., 2014; Maloney et al., 1999). Osteophytes may fracture and produce loose bodies in the elbow joint.

Olecranon stress fracture

A transverse or oblique olecranon stress fracture is typically a result of increased stress on the olecranon as the elbow undergoes a valgus extension load (Kancherla et al., 2014). Both repetitive microtrauma caused by olecranon impingement or excessive triceps tensile stress have also been implicated as etiologies (Cain et al., 2003).

Olecranon bursitis

Tenderness, thickening, and fluctuance over the tip of the olecranon are indicative of olecranon bursitis. These findings occasionally may be associated with a bony prominence at the tip of the bone. Olecranon bursitis caused by friction injury and leads to limitation of ROM because of swelling and pain.

Triceps tendon rupture

Triceps tendon can be ruptured by closed trauma and defects can be recognized posterior to elbow. Patients cannot raise their elbow overhead against gravity. Surgical repair or reconstruction is warranted.

Anterior elbow pain

The anterior elbow pain commonly originates from tendons, capsules, and nerves. Biceps tendon injuries and median nerve compression are possible sources for anterior elbow pain.

Biceps tendon injuries

Distal biceps tendon injuries can be classified as acute traumatic rupture of the tendon and chronic tendinitis (Alberta and Elattrache, 2008). Rupture of the biceps tendon usually occurs in young or middle-aged men who experience a sudden eccentric load applied with the elbow flexed. Patients feel weakness of elbow flexion, particularly involving activities that require supination of the forearm. Chronic tendinitis of the biceps occurs with overuse. It generally manifests as chronic pain in the antecubital fossa particularly with activities requiring elbow flexion and supination.

Median nerve compression

In the antecubital fossa, median nerve travels medial to the brachial artery and biceps tendon and under the lacertus fibrosis. In the proximal forearm, the median nerve passes between humeral and ulnar heads (origins) of pronator teres. Median nerve compression in the antecubital fossa or/and proximal forearm is also a common cause of anterior elbow pain in an athlete that may present similarly to biceps pathology. Sports with repetitive pronation and flexion activities may cause compression neuropathy of the nerve. Patients may present with weakness of wrist and finger flexors (especially flexor pollicis longus and index flexor digitorum profundus) and numbness in the thumb, index, and middle fingers.

Abbreviations

AIN	Anterior interosseous nerve
AL	Annular ligament
AMCL	Anterior bundle of MCL
BB	Biceps brachii
BR	Brachioradialis
ECRB	Extensor carpi radialis brevis
ECRL	Extensor carpi radialis longus
HRJ	Humeroradial joint
HUJ	Humeroulnar joint
IOM	Interosseous membrane
LCL	Lateral collateral ligament
LUCL	Lateral ulnar collateral ligament
MCL	Medial collateral ligament
PIN	Posterior interosseous nerve
PLRI	Posterolateral rotatory instability
PMCL	Posterior bundle of MCL
PRUJ	Proximal radioulnar joint
RCL	Radial collateral ligament

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Chapter 13

Kinesiology of the wrist and the hand

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Kinesiology of the wrist

Introduction

The wrist is considered the most complex joint of the body, both anatomically and physiologically. It controls the length-tension relationship of the wrist and hand muscles during various daily living activities. The wrist consists of a total of eight carpal bones, including the scaphoid, lunate, triquetrum, pisiform, trapezoid, trapezium, capitate, and hamate, the distal ends of the radius and ulna and basis of the five metacarpals (Fig. 13.1).

This multiarticular joint consists of 27 joints, including radiocarpal/ulnocarpal, midcarpal, and intercarpal joints. There is a wide network of ligaments that play an important role in joint stability and normal alignment of the carpal bones during wrist movements. This ligament network and shapes of the bones facilitated the carpal bone movements, since there are few muscle insertions on the wrist. Wrist motion is essential for the optimal performance of activities of daily living (ADLs) and vocational activities. The wrist joint permits flexion, extension, radial and ulnar deviation, and axial rotation movements with the biaxial structure. Recent studies have also reported that many ADLs are performed using an oblique axis defined by the dart throwing motion (DTM) (Wolfe et al., 2006; Moritomo et al., 2007; Moritomo et al., 2014). This chapter reviews the complex structure of the wrist, including the information that is important to understand normal wrist kinematics, and describes the kinematics of the wrist in common pathologic wrist conditions.

Osteology

Distal radius

The radius widens distally in the medial and lateral directions. The dorsal surface has a tubercle that is known as the Lister's tubercule, with grooves on either side of it for the extensor pollicis longus (EPL) tendon on its ulnar side and for the extensor digitorum communis (EDC) and the extensor indicis proprius (EIP) tendons on its radial side. The dorsal tubercle serves as a pulley to redirect the pull of the EPL. The radial surface of the radius is roughened and the styloid process is easily palpated on the radial surface of the wrist. Ulnar notch or sigmoid notch is located on the ulnar surface of the distal radius, which is the articulating surface for the distal radioulnar joint (DRUJ) (Fig. 13.2). Its shape is variable and appears to be influenced by the relative length of the ulna. The distal radius rotates about the ulnar head via concave sigmoid notch. The shape of articular surfaces influences the stability of the DRUJ. The palmar surface of the distal radius is the site of the wrist capsule and palmar radiocarpal ligaments.

Distal radius has three articular surfaces, which are concave in both mediolateral and anteroposterior directions: sigmoid notch, scaphoid fossa, and lunate fossa (Fig. 13.2). The scaphoid and lunate fossa are separated by the dorsal−palmar ridge. The distal articular surface of the radius has an average radial inclination of 22 degrees (ulnar tilt) and a palmar tilt of 11 degrees.

This ulnar tilt accounts for the greater amounts of ulnar deviation than the radial deviation. The palmar tilt allows greater flexion than extension at the wrist. Besides, in a study of Karnezis et al., an inverse relationship was

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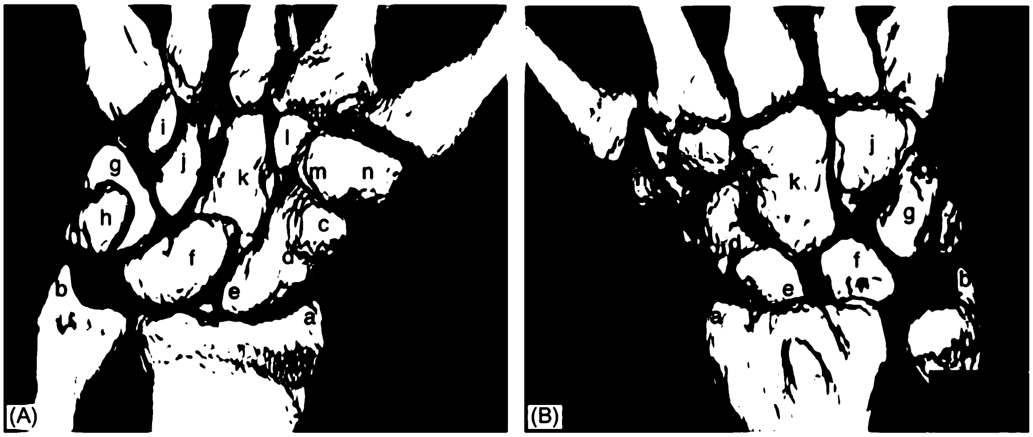


FIGURE 13.1 Palmar (A) and dorsal view (B) of the carpus describing the osteology. Landmarks on the 3D CT reconstruction are —(a) radial styloid, (b) ulnar styloid, (c) scaphoid tubercle, (d) waist of scaphoid, (e) proximal pole of scaphoid, (f) lunate, (g) triquetrum, (h) pisiform, (i) hook of hamate, (j) hamate, (k) capitate, (l) trapezoid, (m) tubercle of trapezium, (n) trapezium (Reddy and Compson, 2005).

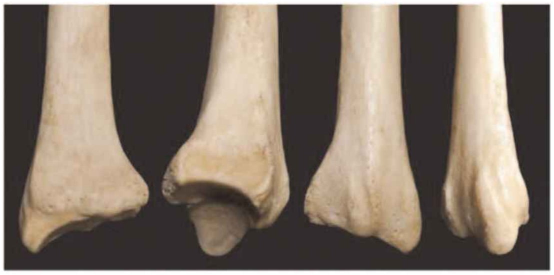


FIGURE 13.2 The four surfaces (anterior, medial, posterior, and lateral) of the distal radius are shown from left to right, along with the styloid process and dorsal tubercle (Obert et al., 2015).

observed between the palmar tilt and the amount of the maximum joint reaction force (Karnezis, 2005). The ulnar and the palmar tilts also help explain the direction of carpal subluxation, ulnar, and palmar, in patients with rheumatoid arthritis.

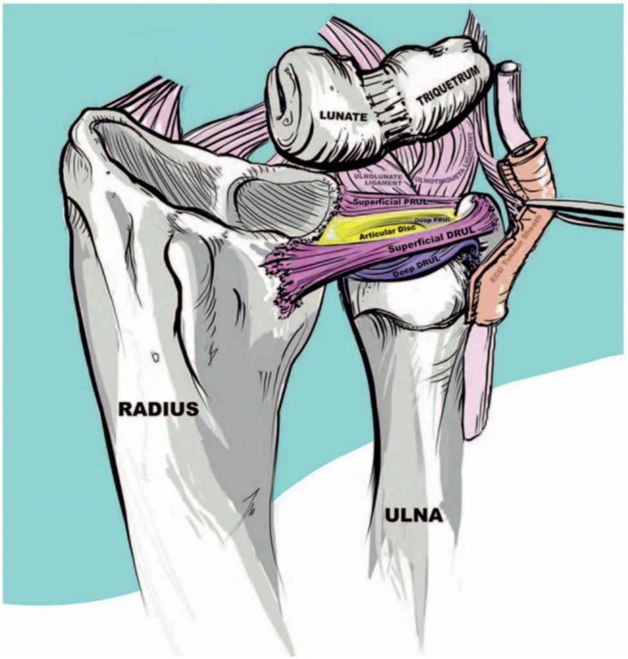


FIGURE 13.3 The head of the ulna articulates with the radius and the TFCC between the ulna and the carpal bones (Altman, 2016). *TFCC*, Triangular fibrocartilage complex.

Distal ulna

The head of the ulna articulates with the radius and the triangular fibrocartilage complex (TFCC) between the ulna and the carpal bones (Fig. 13.3). The articular surface of the ulna is flatter than that of the radius in the anteroposterior direction, allowing gliding motions between the two bones. The ulnar head is easily palpated dorsally with the forearm pronated. The ulnar styloid is the medial bony projection of the distal ulna, and it is palpated on the ulnar aspect of the wrist when the forearm is supinated. The fovea is a slight depression at the base of the styloid process providing attachment for the TFCC.

The length of the ulna varies with the length of the radius. The relative length of the distal articular surfaces of the radius and ulna is referred to as ulnar variance (Fig. 13.4). Positive ulnar variance describes where the distal articular surface of the ulna is more distal when compared to the articular surface of the radius, and the negative ulnar variance is opposite (Fig. 13.5).

Ulnar variance changes with forearm position and power grip. During pronation the radius axially shortens and translates palmarly relative the distal ulna. The reverse motion occurs during supination (Fig. 13.6).

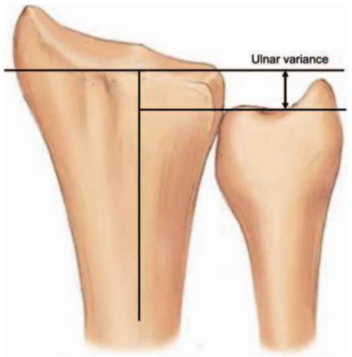


FIGURE 13.4 The relative length of the distal articular surfaces of the radius and ulna is referred as ulnar variance (Mulders et al., 2017).

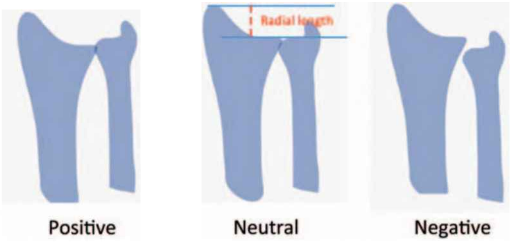


FIGURE 13.5 Positive ulnar variance and negative ulnar variance (Macaulay et al., 2017).

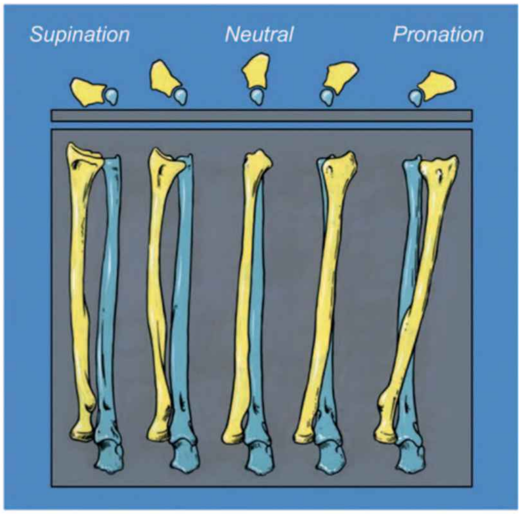


FIGURE 13.6 Ulnar variance changes with forearm position and power grip. During pronation the radius axially shortens and translates palmarly relative the distal ulna. The reverse motion occurs during supination (Huang and Hanel, 2012).

Therefore full forearm pronation and power grip increases ulnar variance, while full forearm supination decreases it as the radius moves distally during supination. This change in relative lengths of the radius and ulna affects the tension in the interosseous membrane during pronation and supination. Supination generates greater tension in the interosseous membrane than pronation (Garcia-Elias, 1998). Unver et al. (2004) suggested that ulnar deviation range of motion is greater in individuals with a negative ulnar variance.

The effects of ulnar variance on the wrist biomechanics

The ulnar variance affects the amount of force transmitted to the distal radius and the TFCC. Ulnar variance changes related to forearm rotation and power grip may be 2–3 mm (Chidgey, 1995). Changes of this magnitude demonstrate the increased load transmission through ulnocarpal articulation (Fig. 13.7). Most of the ADLs involving rotation and grip result large load transmission across TFCC (Spies and Unglaub, 2018).

A positive ulnar variance (long ulna) is defined when the distal articular surface of the ulna extends more than 1 mm beyond the radius margin at the DRUJ. Positive variance can lead to ulnar sided wrist pain due to perforation of the TFCC and ulnar impaction syndrome (Fig. 13.8), (De Smet, 1994). It may be congenital due to growth disorder as with Madelung's disease when there is premature growth arrest at the volar/ulnar physis of the distal radius (Fig. 13.9). Acquired conditions may be observed in patients following distal radius fractures that may have impacted, be malunited, or have caused growth arrest such as in "gymnast's wrist" (Tolat et al., 1992). Patients who have undergone radial head resections may also exhibit positive ulnar variance as the radius migrates proximally (Fig. 13.10). These patients may be prone to more degenerative changes in the ulna, the medial carpal bones, and the intervening disk.

Negative ulnar variance (short ulna) is likely to increase the shear forces and stress on the lunate predisposing the lunate to injury. Increased pressure inside the bone along with increased stresses on the lunate can affect the blood supply leading to avascular necrosis of the lunate (Kienböck's disease) (Fig. 13.11), (De Smet, 1994). In the cases of ulnar variance the patient may need to learn joint protection strategies to reduce the magnitude of the loads sustained at the wrist.

Carpal bones

The carpus is composed of eight bones that are arranged into two rows horizontally and three columns vertically. Horizontal section of the carpus subdivides the carpus into proximal and distal row. The proximal row contains the scaphoid, lunate, triquetrum, and pisiform and the distal row consists of the trapezium, trapezoid, capitate, and hamate (Fig. 13.12). The proximal row acts as an intercalated segment between the radius and the distal carpal

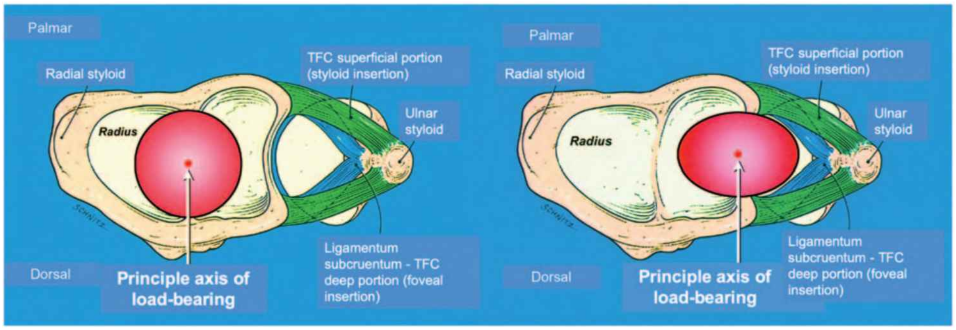

Palmar
Radial styloid
TFC superficial portion (styloid insertion)
Radius
Ulnar styloid
Dorsal
Principle axis of load-bearing
Ligamentum subcruentum - TFC deep portion (foveal insertion)
Palmar
Radial styloid
TFC superficial portion (styloid insertion)
Radius
Ulnar styloid
Dorsal
Principle axis of load-bearing
Ligamentum subcruentum - TFC deep portion (foveal insertion)

FIGURE 13.7 Changes of this magnitude demonstrate the increased load transmission through ulnocarpal articulation (Kleinman, 2007).

FIGURE 13.8 Ulnar impaction syndrome (Sammer and Rizzo, 2010).

FIGURE 13.10 Radial head resections may also results in positive ulnar variance (Flowers and LaStayo, 2007).

FIGURE 13.9 Madelung's disease (Kozin and Zlotolow, 2015).

FIGURE 13.11 Increased stresses on the lunate can affect the blood supply leading to avascular necrosis of the lunate (Kienböck's disease) (Lutsky and Beredjiklian, 2012).

row. There are three columns vertically when considering the mechanical axis of transmission of forces between the radius and the carpometacarpal (CMC) complex. The first column includes scaphoid, trapezium, and trapezoid; the second column includes capitate and lunate; the third column consists of triquetrum, pisiform, and hamate.

Scaphoid

The scaphoid or navicular is located in the most radial aspect of the proximal carpal row. The scaphoid contacts four carpal bones and the radius (Fig. 13.13). It functions as a bridge between the proximal and distal carpal rows. There is an angle of 30 degrees between the proximal and distal poles in the lateral view and an angle of 40 degrees in the frontal view (Fig. 13.14). The frontal and sagittal plane also makes an angle of 45 degrees with the radial axis. Due to the 45 degree angle between the scaphoid and the radius, scaphoid tends to flex when objected to axial loading (Fig. 13.15). Ligamentous structures resist this tendency.

The scaphoid consists of three parts, including two convex surfaces (proximal and distal pole) and the waist (Fig. 13.15). The proximal pole articulates with the lunate and the radius. The proximal pole serves as a pivot for the flexor carpi radialis (FCR) muscle. FCR passes through the medial groove and inserts to the basis of scaphotrapeziotrapezoidal (STT) joint and 2–3 metacarpal basis (Fig. 13.16). Extrinsic and intrinsic ligaments

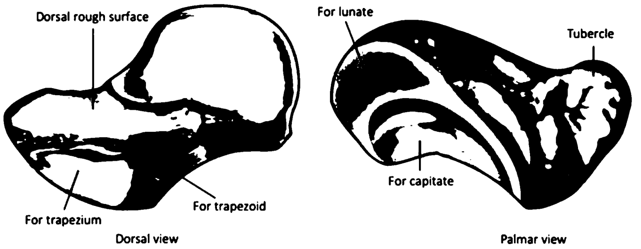


FIGURE 13.12 Anatomy of the scaphoid (Panchal-Kildare and Malone, 2013).

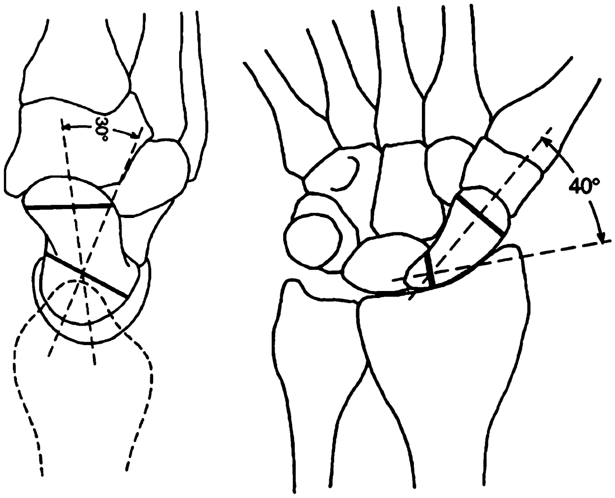


FIGURE 13.13 There is an angle of 30 degrees between the proximal and distal poles of the scaphoid in the lateral view and an angle of 40 degrees in the frontal view (Trumble and Vo, 2001).

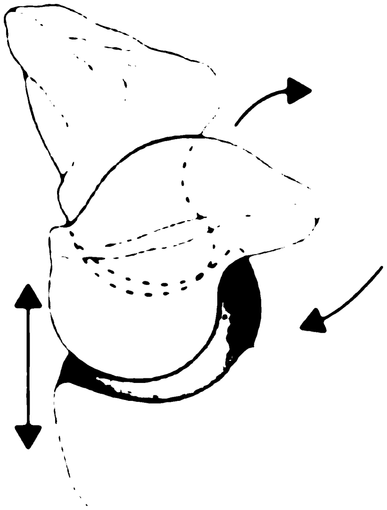


FIGURE 13.14 Due to the 45 degree angle between the scaphoid and the radius, scaphoid tends to flex when objected to axial loading (McGee, 2003).

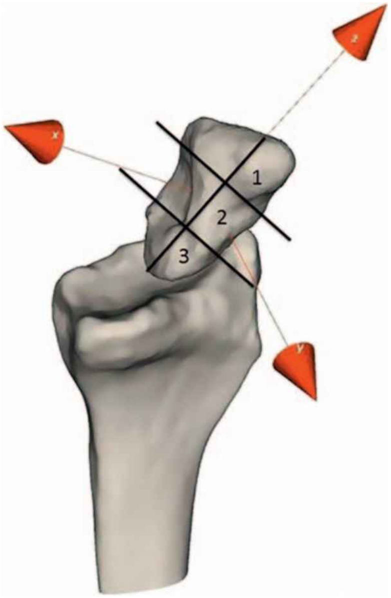


FIGURE 13.15 The scaphoid consists of distal pole (1), the waist (2) and proximal pole (3) (de Roo et al., 2018).

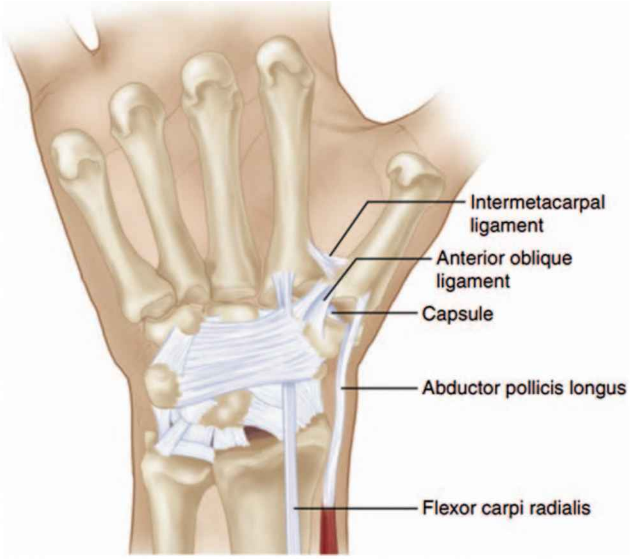


FIGURE 13.16 FCR passes through the medial groove and inserts to the basis of STT joint and 2–3 metacarpal basis (Saito et al., 2017). *FCR*, Flexor carpi radialis; *STT*, scaphotrapeziotrapezoidal.

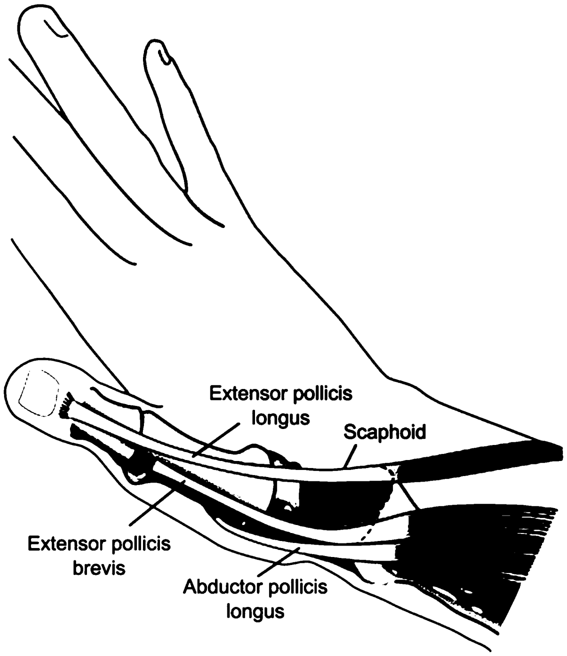


FIGURE 13.17 The lateral part forms the floor of the anatomical snuffbox (Seidenberg and Beutler, 2008).

strongly attached the scaphoid providing stability during wrist movements. The medial part of the waist articulates with the head of the capitate. The lateral part forms the floor of the anatomical snuffbox (Fig. 13.17). The distal pole has a relatively rounded face and articulates with trapezium and trapezoideum. The scaphoid has a large tubercle anteriorly that corresponds to the palmar projection of the distal pole. This tubercle can be palpated by the radial side of the palm. The flexor retinaculum and abductor pollicis brevis (APB) muscle insert to the scaphoid tubercule.

The major blood supply to the scaphoid is via radial artery. The proximal group enters through the dorsal ridge of the scaphoid waist and provides 70%–80% of the interosseous vascularity. The distal group enters through distal tubercule and provides 20%–30% of the interosseous vascularity (Fig. 13.18). There is a collateral circulation to the scaphoid via the dorsal and volar branches of the anterior interosseous artery. There are no vessels entering the proximal part, which explains the nonunion, pseudoarthrosis, and necrosis of the scaphoid in the case of fractures at this level. The volar operative approach is suggested that it may be least traumatic to the proximal pole's blood supply (Gelberman and Menon, 1980).

Since the scaphoid is located between the radius and the trapezo-trapezoidal joint, it is under important compressive constraints. The scaphoid transmits 60% and the lunate 40% of these axial constraints (Fig. 13.19). These constraints tend to flex the scaphoid due to its angle of 45 degrees with the radius. Flexion tendency of the scaphoid is counteracted by STT ligament, the scaphocapitate (SC) ligament, the radioscaphocapitate ligament, and the FCR muscle (Fig. 13.20).

Scaphoid fractures

The scaphoid and the radius are located in the path of most of the force transmission through the wrist. Scaphoid fractures are among the most common upper extremity injuries, which occur form falling on an extended and radially deviated wrist. Healing is often hindered if the fracture is at the proximal pole of the scaphoid because of the minimal blood supply to this region (Grewal et al., 2016). Thirty-five to eighty six percent of the scaphoid fractures are presented with associated ligamentous and/or osteochondral injuries (Caloia et al., 2008).

Lunate

Lunate has a shape of a lunar crescent. It is located in the center of the proximal carpal row, between the scaphoid and triquetrum. Its anterior horn is bigger than the posterior horn (Fig. 13.21). The lunate axis is parallel with the radial axis in the neutral wrist position and two horns become at the same height. The proximal face of the lunatum is convex and it articulates with the radius. The distal face of the lunate is deeply concave and articulates with the capitate and hamate. Its lateral side articulates with the scaphoid and its medial side articulates with the triquetrum (Fig. 13.22), (Watson and Weinzweig, 2001; Trumble et al., 2006; Neumann, 2013).

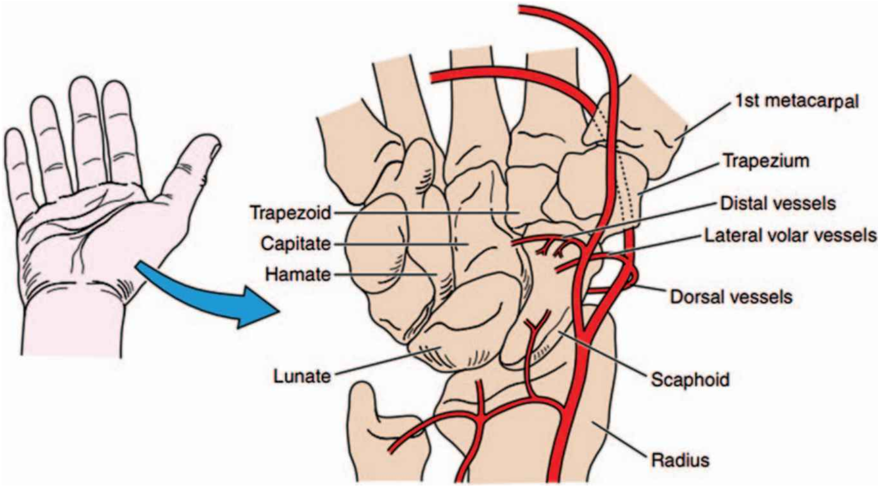


FIGURE 13.18 The distal group enters through distal tubercule and provides 20%–30% of the interosseous vascularity (Magee et al., 2015)

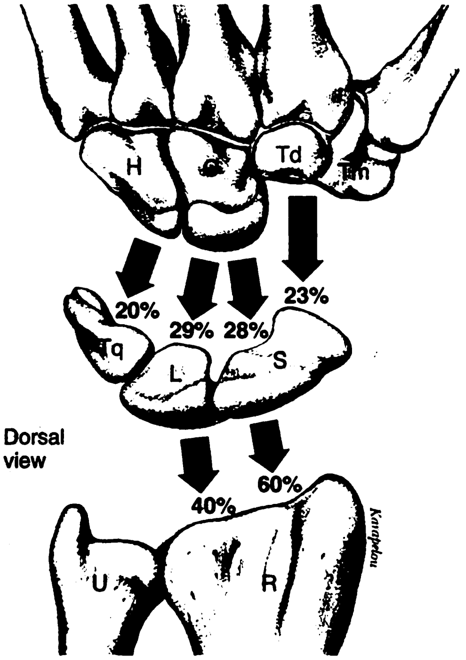


FIGURE 13.19 The scaphoid transmits 60% and the lunate 40% of these axial constraints (Powell et al., 2016).

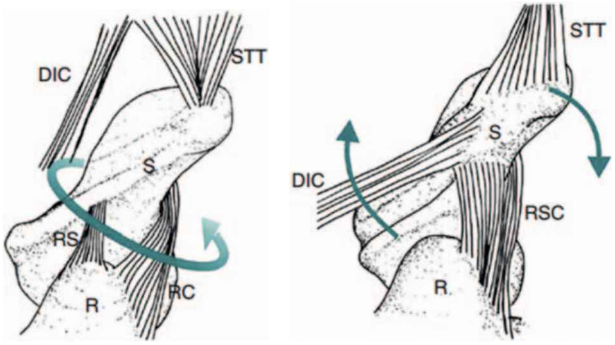


FIGURE 13.20 Flexion tendency of the scaphoid is counteracted by STT ligament, the scaphocapitate ligament, the radioscaphocapitate ligament, and the flexor carpi radialis muscle (Buijze and Jupiter, 2017). *STT*, Scaphotrapeziotrapezoidal.

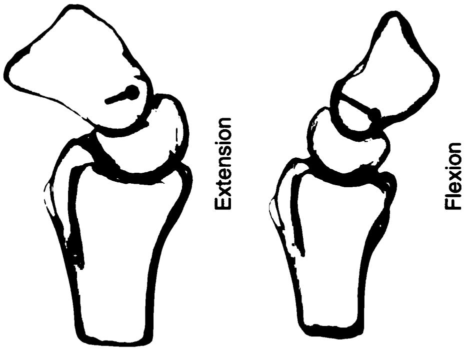


FIGURE 13.21 Lunate has a shape of a lunar crescent and its anterior horn is bigger than the posterior horn (Blankenhorn et al., 2007).

Lunate morphology

Lunate morphology affects the carpal kinematics. Type 1 lunate leads to greater motion at the radiocarpal joint during wrist flexion and extension than a type II lunate. Type II lunate lead to less motion at the midcarpal joint during wrist flexion and extension (Bain et al., 2015).

Lunate pathologies

Lunate dislocation

The volar surface of the lunate is broader than its dorsal surface. The narrower dorsal surface can easily slip volarly with little obstruction, while the broader volar surface is less likely to protrude dorsally. Therefore dislocations of the lunate are usually in the volar direction.

The lunate plays an important role in stabilizing the entire carpus, as it is located in the center of the proximal

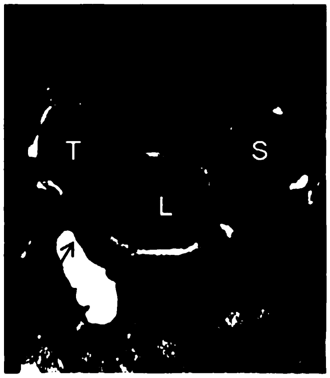


FIGURE 13.22 Its lateral side articulates with the scaphoid and its medial side articulates with the triquetrum (Porteous et al., 2012).

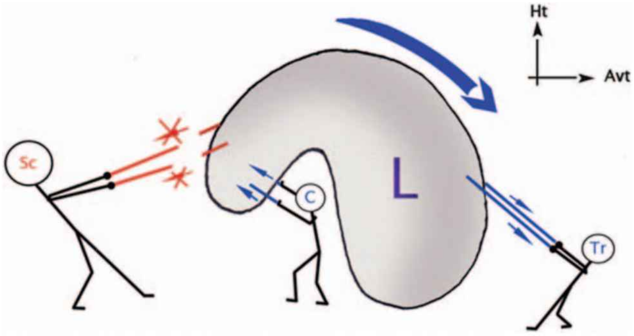


FIGURE 13.24 In the case of the SLIL injury the lunate goes into extension due to intact LTIL, Lunotriquetral interosseous ligament (Mesplie, 2015). *SLIL*, Scapholunate interosseous ligament.

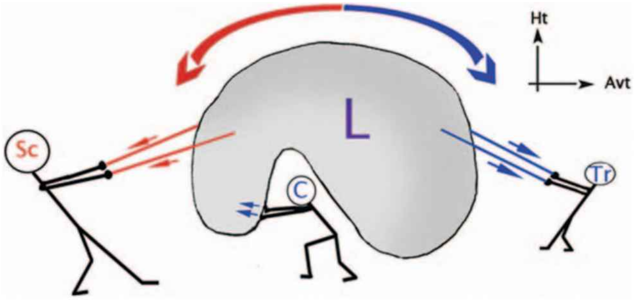


FIGURE 13.23 There are two opposite forces acting on the lunate (Mesplie, 2015).

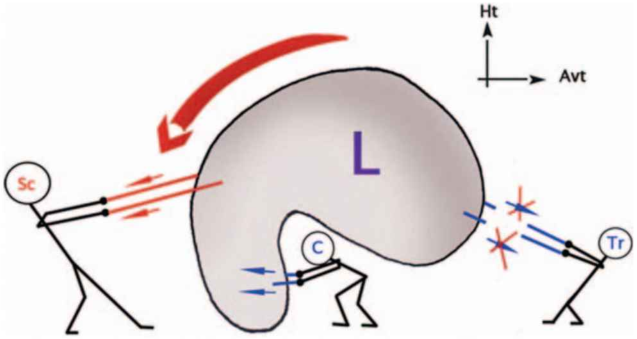


FIGURE 13.25 In the case of LTIL injury the lunate goes into flexion (Mesplie, 2015). *LTIL*, Lunotriquetral interosseous ligament.

carpal row. It can be palpated just distal and ulnar to the Lister's tubercule with the wrist slightly flexed. The tubercule is located just proximal to the scapholunate interval. No muscles attach to the lunate. Therefore stability of the lunate depends primarily upon the shape of the articular surfaces and the ligamentous structures. There are two opposite forces acting on the lunate (Fig. 13.23). When subjected to axial loading scaphoid tend to flex and triquetrum and capitate tend to extend. Therefore scaphoid brings the lunate to flexion, and the triquetrum and the capitate bring it to extension. The effects of these opposite forces on the lunate provide better understanding of the instability patters following scapholunate interosseous ligament (SLIL) and lunotriquetral interosseous ligament (LTIL) injury. In the case of SLIL injury the effect of the scaphoid on the lunate will be lost and the lunate will go to extension due to intact LTIL (Fig. 13.24). This instability pattern describes as dorsal intercalated segmental instability (DISI). In the case of LTIL injury the lunate will go to flexion or volar intercalated segment instability (VISI) (Fig. 13.25).

Kienböck's disease

Kienböck's disease is described as the osteonecrosis of the lunate. It is often referred to as lunatomalacia. However, its cause remains unknown; it is proposed that the increased pressure on the lunate is associated with the Kienböck's disease. Repetitive loading of the lunate may cause this condition which is commonly seen within young men and middle-aged women (McCague, 2014; Dias, 2010). A significant association is found between negative ulnar variance and Kienböck's disease since negative variance is present in 75% of individuals with Kienböck's disease. However, most of the individuals with negative ulnar variance may not have the condition (Hong et al., 2019). Decompressive procedures such as radial shortening or ulnar lengthening are suggested to control pain and to prevent further collapse of the lunate. Disruption of the blood supply of the lunate plays an important role in the pathogenesis of the condition. It leads to bone infarction, necrosis, and microfractures. The vascular supply of the lunate greatly contributes to the formation of Kienböck's disease. In 70% of patients, multiple vessels supply both volarly and dorsally. On the volar surface, these include branches from the anterior interosseous artery in 70% and a branch of the palmar intercarpal arch in 70% of patients. On the dorsal surface, dorsal perforating branches of the anterior interosseous artery are seen in 86% of patients and dorsal branch from the dorsal intercarpal arch in 50% of patients. In the remaining 30%, there is only a single vessel volarly and dorsally, which predisposes to osteonecrosis of the lunate (O'Laughlin, 2010).

Triquetrum

Triquetrum has a shape of a pyramid. Its proximal and the ulnar parts articulate with the fibro-cartilaginous disk during ulnar deviation. The radial side articulates with the lunate. Its inferior part articulates with the hamate (Fig. 13.26). This part is in contact with the hamate in full ulnar deviation. The triquetrum is palpable on the ulnar side of the wrist during radial deviation.

Pisiform

Pisiform articulates loosely with the palmar surface of the triquetrum. As it is a sesamoid bone, it plays a small role in wrist kinematics. Flexor carpi ulnaris (FCU) muscle inserts on it. Pisiform increased the FCU efficacy by improving its tendinous angle (Fig. 13.27), (Watson and Weinzweig, 2001; Standring et al., 2005; Coll et al., 2013). It provides attachments for many other ligamentous and muscular structures of the wrist and hand, including transverse carpal ligament and pisohamate ligament.

Trapezium

Trapezium has an asymmetrical shape. The proximal side is slightly concave articulating with the scaphoid. This articulation places the trapezium out of the plane of the other carpal bones of the distal row. Thus the thumb lies at about a 45 degree angle with the second metacarpal. The distal side articulates with the first metacarpal and the internal side articulates with the trapezoid and second metacarpal. The thin and sharp tubercle is projected by the palmar surface of the trapezium. Transverse carpal ligament, deep portion of the flexor pollicis brevis (FPB), and opponens pollicis (OP) muscles inserts on it (Fig. 13.28), (Watson and Weinzweig, 2001; Standring et al., 2005; Coll et al., 2013).

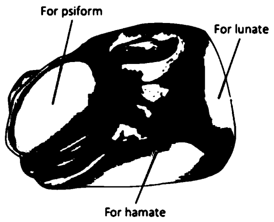


FIGURE 13.26 Anatomy of the triquetrum (Panchal-Kildare and Malone, 2013).

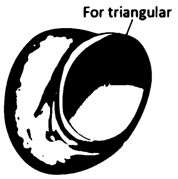


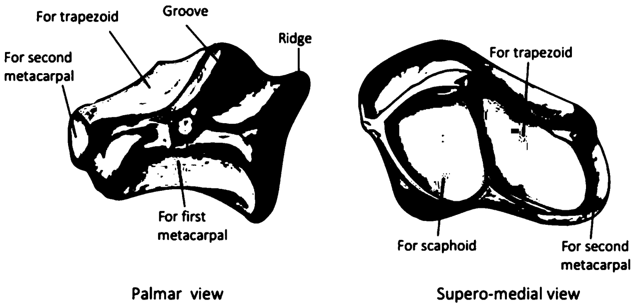
FIGURE 13.27 Anatomy of the pisiform (Panchal-Kildare and Malone, 2013).

Trapezoid

Trapezoid is a small bone between the capitate and trapezium. The proximal surface of the trapezoid is slightly concave articulating with the scaphoid and distal part articulates with the second metacarpal. The stable base is important to the role of second metacarpal during powerful pinch. Its internal part articulates with the capitate and its external part articulates with the trapezium (Fig. 13.29). FPB and adductor pollicis (AddP) muscles insert on it.

Capitate

Capitate is the largest carpal bone locating in the center of the wrist acting as a keystone of the carpal arch. Many wrist ligaments attach to it. It articulates with every other carpal bone except for the triquetrum. The head of the capitate articulates with the deep concave surfaces of the scaphoid and lunate (Fig. 13.30). The capitate is in line with the radius, the lunate, and the base of the third metacarpal. The rotation axis passes over the capitate. Distal face of capitate makes a rigid



Palmar view
Supero-medial view

FIGURE 13.28 Anatomy of the trapezium (Panchal-Kildare and Malone, 2013).

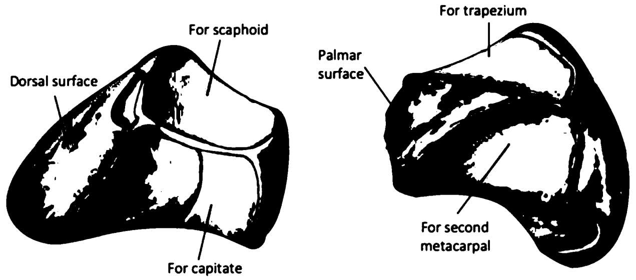


FIGURE 13.29 Anatomy of the trapezoid (Panchal-Kildare and Malone, 2013).

joint with the second–fourth metacarpals. These rigid articulations improve the longitudinal stability of the wrist, allowing the third metacarpal and capitate to act as a single column (Watson and Weinzweig, 2001; Standring et al., 2005; Coll et al., 2013). FPB and AddP muscles insert on it.

Hamate

Hamate has a pyramid-shape. The distal side articulates with the fourth and fifth metacarpals. This articulation helps to maintain joint mobility in the ulnar side, in particular in the grip position. The apex of the hamate is in contact with the concave face of the lunatum. Hamate hook and pisiform form medial attachment surface for the transverse carpal ligament (Fig. 13.31), (Watson and Weinzweig, 2001; Coll et al., 2013). Flexor digiti minimi (FDM) and opponens digiti minimi (ODM) insert on it.

Sesamoid bones

Sesamoid bones are small round or oval shaped nodules that are located within certain tendons. Typically there are five sesamoid bones in each hand; two at the metacarpophalangeal (MCP) joint of the thumb, one at the interphalangeal (IP) joint of the thumb, one at the MCP joint of the index finger on the radial side, and one at the MCP joint of the little finger on the ulnar side. Sesamoid bones of the thumb MCP joint located imbedded within the tendons of the FPB and the AddP. These bones act as a pulley by altering the lines of pull of the tendons in which they insert, consequently improving the efficacy of the muscles (Yammine, 2014).

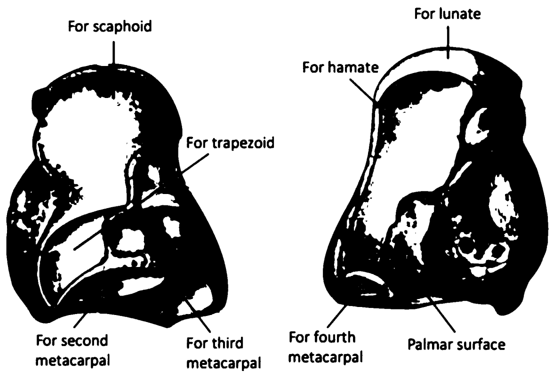


FIGURE 13.30 Anatomy of the capitate (Panchal-Kildare and Malone, 2013).

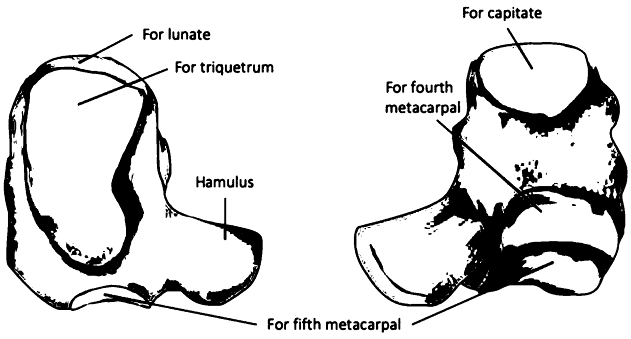


FIGURE 13.31 Anatomy of the hamate (Panchal-Kildare and Malone, 2013).

Artrology

Wrist joint structure

The wrist joint is multiarticular and includes two compound joints, radiocarpal and midcarpal joints (8). The combination of midcarpal and radiocarpal joint motion is responsible for the total range of wrist motion (Fig. 13.32). The global wrist motion was defined as the rotation of the capitate with respect to the radius (de Lange et al., 1985). The biaxial joint structure of the wrist allows flexion/extension and radial/ulnar deviation (12) (Berger, 1997; Dobyns and Linscheid, 1997; Neumann, 2013). The normal wrist extension is about 85 degrees and flexion is about 85 degrees. The radial deviation is about 15 degrees and ulnar deviation is about 45 degrees. The two-degree of freedom motion of the wrist is facilitated by six-degree of freedom of the carpal articulations. The relative contributions of the radiocarpal and midcarpal joints to the overall global flexion of the wrist are not similar. The midcarpal joint accounts for approximately 33% of global wrist extension, while the radiocarpal joint

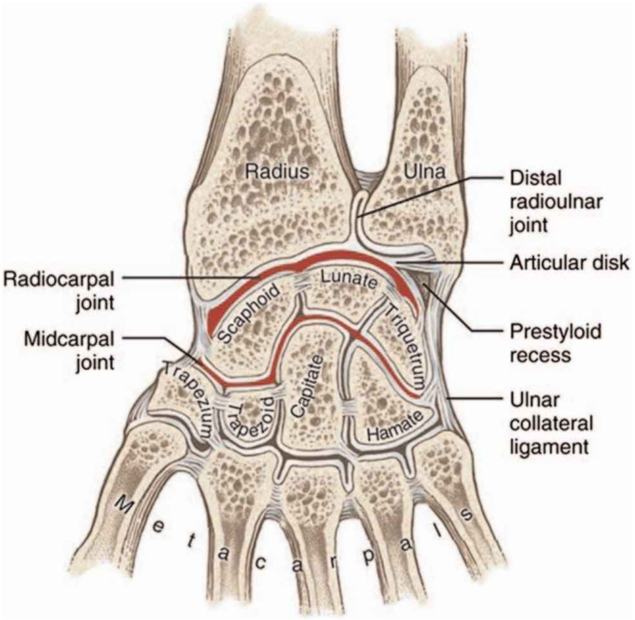


FIGURE 13.32 The radiocarpal and midcarpal joints of the wrist (Mansfield and Neumann, 2014).

is responsible for 66%. In flexion the midcarpal joints contribute 60% of the overall motion and the radiocarpal joint contributes 40%. Sixty percent of the ulnar deviation is performed in the radiocarpal joint while 60% of the radial deviation is in the midcarpal joint.

Articulations

Radiocarpal joint

The radiocarpal joint is an ellipsoid type joint between the radius and the scaphoid and lunate (14). The triquetrum contributes to radiocarpal articulation indirectly by articulating with the articular disk of the TFCC. It is in contact with the TFCC in full ulnar deviation (12). With wrist motion the convex articular surface of the proximal carpal row slides on the concave distal radius and articular disk in the direction opposite the physiological motion of the hand.

The articular surface of the radius with the articular disk of the TFCC is biconcave, and the articular surface of the proximal carpal row is biconvex, including scaphoid, lunate, and triquetrum. However, the radiocarpal joint is a biaxial joint, it demonstrates less congruency between the reciprocal articulating surfaces due to the individual roles of the carpal bones in the joint mechanics. The contact between the scaphoid, the lunate, and the radius is not constant and uniform. The contact area between the scaphoid and the radius is greater than the contact area between lunate and the radius (Patterson and Viegas, 1995; Nakamura, 2017). Change of the joint contact distribution is connected with the motion of carpal bones. The joint contact surfaces of the scaphoid and the lunate on the distal radial articular surface are changed minimally during forearm rotation (Chen and Tang, 2013).

In general, 80% of the axial compressive force is transmitted through the radiocarpal joint (radioscaphoid and radiolunate joints) and 20% through the TFCC. A nonlinear relation was found between increasing loads and greater overall contact areas (Viegas et al., 1989). In the radiocarpal joint the general distribution of the contact between the scaphoid and lunate contact areas was consistent under loading with the scaphoid involving 60% of the total contact area and the lunate involving 40% (25). Viegas et al. (1987) investigated the load characteristics of the wrist with pressure-sensitive film under a load of 103 N in the cadaver wrist. When the wrist changes from flexion to extension, contact areas shift from the volar site to the dorsal site. Viegas et al. (1987) reported that the scaphoid contact area was greater than the lunate and was greatest in ulnar deviation. Pillai et al. (2007) also reported that the values of the contact areas of the radioscaphoid and radiolunate joints were 41.6 and 10.2 mm^2, respectively. The results demonstrate that the contact mechanism of the radioscaphoid joint is different from that of the radiolunate joint. The scapholunate contact area ratio was greater in ulnar deviation and extension. Therefore contact areas in the radiocarpal joint are the highest in the wrist extension and ulnar deviation in which the grip force is produced maximally. Furthermore, Viegas et al. investigated the effect of the magnitude of the axial loading on articular cartilage mechanics. Loads less than 11 kg is resulted in contact area approximately 20% of the surface area. When a load of 22 kg is applied, the contact area increases to 40% causing articular cartilage deformation. Loads greater than 22 kg did not increase the overall contact areas suggesting that at loads of this magnitude maximally compressed the articular cartilage of the wrist (Viegas et al., 1989).

The lack of inherent stability of the joint is compensated by the support of the strong ligamentous network and the capsule. The radiocarpal joint, together with the midcarpal joint, is surrounded by a loose but strong capsule supported by numerous extrinsic and intrinsic ligaments (Fig. 13.33). The capsule attaches on the radius, the TFCC, and the proximal carpal row. The capsule of the radiocarpal joint has an inner surface composed of synovial tissue. There are numerous palmar and dorsal ligaments on this inner surface (Dobyns and Linscheid, 1997; Watson and Weinzweig, 2001).

Midcarpal joint

The midcarpal joint is anatomically distinct from the radiocarpal joint; however, these two joints are structurally and functionally interdependent. The midcarpal joint is a compound joint between the proximal and distal carpal rows. The midcarpal joint is divided into two distinct regions, radial and ulnar compartments, surrounded by a single joint capsule. The ulnar compartment is composed of convex articular surfaces of capitate and hamate and the concave articular surfaces of the scaphoid, lunate, and triquetrum. The convex head of the capitate is placed in the concave articular surface of the scaphoid and the lunate like a ball-socket joint. It functions as a biaxial structure. With flexion/extension and radial/ulnar deviation, the distal component of the ulnar compartment (capitate and hamate) slides opposite direction to the physiological movement.

The radial compartment is between the convex distal surface of the scaphoid and the concave proximal surface of the trapezium and trapezoideum. This compartment is less involved in the wrist movements than the ulnar compartment. The distal component of the radial compartment (trapezium and trapezoideum) slides in the same direction as the physiological movement during flexion and extension. However, in the radial and ulnar deviation, the proximal carpal bones rock in dorsal and volar direction. This

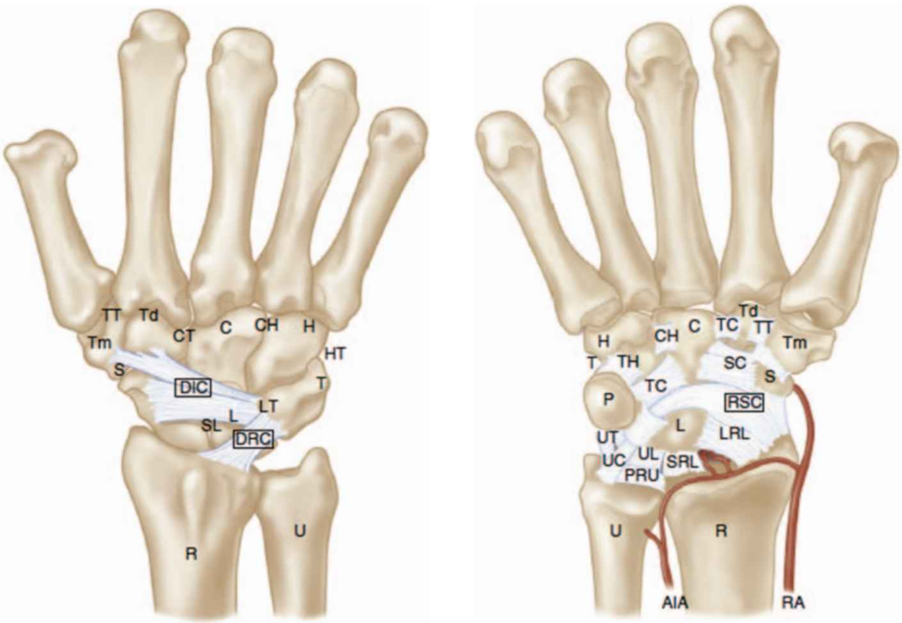


FIGURE 13.33 *AIA*, Anterior interosseous artery; *C*, capitate; *CH*, capitohamate ligament; *CT*, capitotriquetral ligament; *DIC*, dorsal intercarpal ligament; *H*, hamate; *HT*, hamate-triquetral ligament; *L*, lunate; *LRL*, lunotriquetral ligament; *P*, pisiform; *PRU*, palmar radioulnar ligament; *R*, radius; *RA*, radial artery; *RSC*, radioscaphocapitate; *S*, scaphoid; *SC*, scaphocapitate; *SL*, scapholunate; *SRL*, short radiolunate ligament; *T*, triquetrum; *TC*, triquetral capitate ligament; *Td*, trapezoid; *TH*, triquetral hamate ligament; *Tm*, trapezium; *TT*, trapeziotrapezoid ligament; *U*, ulna; *UC*, ulnocapitate ligament; *UL*, ulnolunate ligament; *UT*, ulnotriquetral ligament (Chung, 2008).

motion is most pronounced in the scaphoid. With the radial deviation the scaphoid moves volarly (flexes) and moves dorsally (extends) with the ulnar deviation. Moojen et al. (2002) concluded that because of the passive forces of the ligaments and compression between the adjacent carpals, at 20 degrees of ulnar deviation, the scaphoid rotates dorsally about 20 degrees relative to the radius, and at 20 degrees of radial deviation, the scaphoid moves volarly about 15 degrees, which allows for a few more degrees of radial deviation.

There is an uneven load distribution across the midcarpal joint due to irregular articular surfaces (Patterson and Viegas, 1995). The midcarpal joint, such as the radiocarpal joint, transmits axial loads through a relatively small portion of distinct joint surfaces (Viegas et al., 1993). The contact area on the proximal side of the midcarpal joint was found to consist generally of four areas: the STT, the SC, the lunocapitate, and the triquetrohamate. The greatest load is transmitted through the SC and lunocapitate articulation (28%), and the least is through the triquetrohamate articulation (approximately 20%). Light loads are distributed through a small area of the articular surface in the radiocarpal joint; however, under heavy loads the contact area increases to approximately 35%.

The midcarpal joint is supported by its capsule as well as by the extrinsic and intrinsic ligaments of the wrist. However, the irregularity of the articular surfaces of the midcarpal joint provides some inherent stability to the joint, ligamentous support remains the primary source of stability of the midcarpal joint. The capsule of the midcarpal joint encloses the joint space between the proximal and distal carpal row creating joint spaces for each of the intercarpal articulations except the triquetropisiform articulation, which usually has its own joint capsule and joint space.

Intercarpal joints

The intercarpal joints are the articulations between adjacent carpal bones within each row. These articulations are plane synovial joints and are encapsulated by extensions of the capsule of the midcarpal joint. These articulations are stabilized by the joint capsule and by the extrinsic and intrinsic ligaments. The amount of movement between the carpal bones is small. The carpal bones together form the transverse carpal arch, which is concave palmarly. This arch deepens with wrist flexion and flattens with wrist extension.

Carpal arch

The transverse carpal ligament, or flexor retinaculum, is an accessory ligament that supports the entire carpal arch (Fig. 13.34). It attaches medially to the pisiform bone and hook of the hamate. The lateral portion of the transverse

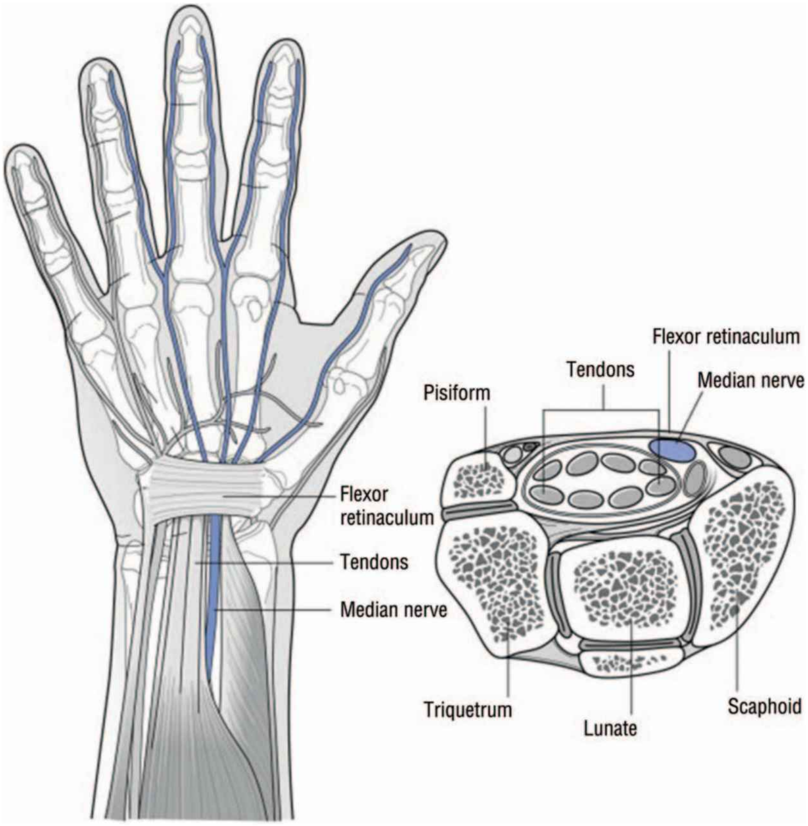


FIGURE 13.34 Flexor retinaculum (Ombregt, 2013).

carpal ligament attaches to the tubercles of the trapezium and scaphoid. The entire transverse carpal ligament bridges the carpal arch, creating the carpal tunnel helping to stabilize the arch and the contents of the tunnel. It is pulled taut in both maximum pronation and maximum supination. Surgical release of the transverse carpal ligament is a common treatment for carpal tunnel syndrome, in which the contents of the carpal tunnel, including the median nerve, are compressed by swelling within the carpal tunnel.

Ligaments

The ligaments of the wrist play a crucial role in guiding and constraining the motion of the carpal bones during movements of the wrist. There are approximately 33 different ligaments in the wrist. In general, the ligaments on the volar and radial side of the wrist are stronger than the ulnar and dorsal side. Hagert et al. found that the radial wrist ligaments consisted of densely packed collagen bundles, whereas the dorsal and ulnar wrist ligaments contained mechanoreceptors and nerves. Consequently, they concluded that radial ligaments may be more important in providing stability to the wrist, whereas others may have proprioceptive functions (Hagert et al., 2007). Innervation of carpal ligaments is provided by the median, ulnar, and radial nerves (Fig. 13.35).

Proprioceptive function of the ligaments

Mechanoreceptors mapped in the wrist ligaments exhibited different innervation patterns with regard to their distribution in the ligaments, their receptor density, and ligaments' structural composition (Petrie et al., 1997; Hagert et al., 2005, 2007; Lin et al., 2006). Innervation patterns of the wrist ligaments suggest that they have different functional roles. The dorsal and triquetral ligaments contain more mechanoreceptors than the radiovolar ligaments, which indicate the critical role they play in the sensorimotor function of the wrist joint (Hagert et al., 2005, 2007). All ligaments connecting the scaphoid to the adjacent carpal bones provide proprioceptive information; however, the most richly innervated ligament is the SLIL (Hagert et al., 2007). The SLIL is innervated from terminal branches of the posterior interosseous nerve (PIN) and, through the radioscapholunate ligament, anterior interosseous nerve (AIN) (Fig. 13.35). The primary sensory nerve ending found in the SLIL is the Ruffini ending (Hagert et al., 2004), which signals during excessive joint positions and rotation, which is when the ligament is at risk of being torn. Innervated ligaments are able to initiate

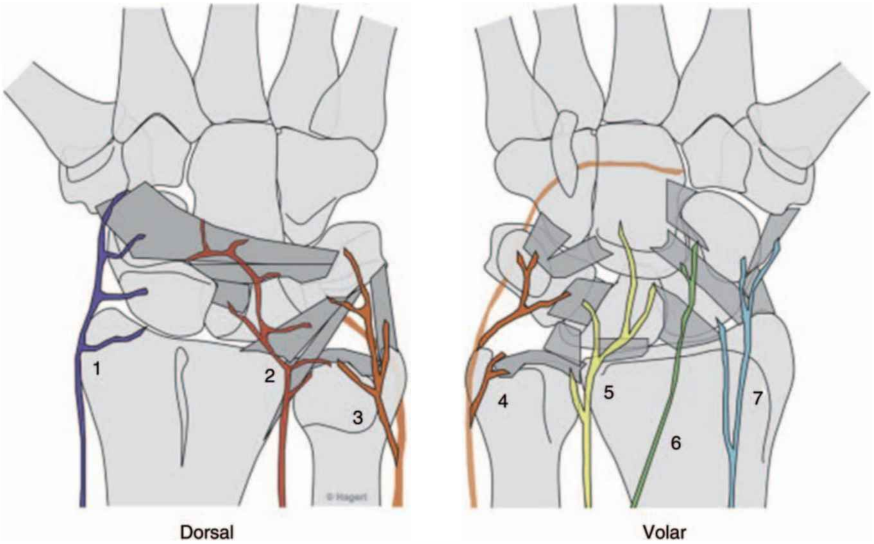


FIGURE 13.35 Innervation of the wrist joint. Dorsal nerves: dorsal sensory branch of the radial nerve (1), terminal branch of the posterior interosseous nerve, the *dorsal interosseous nerve* (2), dorsal sensory branch of the ulnar nerve (3). Volar nerves: deep branches from the ulnar nerve (4), terminal branch of the anterior interosseous nerve (5), volar cutaneous branch of the median nerve (6), and lateral antebrachial cutaneous nerve (7) (Slutsky, 2010).

inhibitory and excitatory muscular activity via ligamentomuscular reflexes. These reflexes stabilize the excessive stress in the ligaments through synergistic muscle activation relevant to the joints (Hagert et al., 2004).

Classification of the ligaments

There is significant variability of the names used to identify the ligaments and also a broad acceptance of their general architecture. These ligaments have been grouped by Taleisnik (1976) into intrinsic and extrinsic. Extrinsic ligaments are extracapsular connecting the radius and ulna to the carpal bones. Intrinsic ligaments are intracapsular connecting carpal bones together (Taleisnik, 1976). Wrist ligaments sustain more elongation before failure than the other ligaments in the body. All of the wrist ligaments have different maximum loads to failure, stiffness, and elongation characteristics during loading. Interosseous ligaments are much stronger than the intrinsic and extrinsic ligaments. Failure occurred at the interosseous ligaments more than 300 N and less than 200 N for extrinsic ligaments. In contrast, they are less stiff than other wrist ligaments sustaining more elongation before failure (Savelberg et al., 1992). Many of the volar and dorsal ligaments are within 5% of their maximum length throughout the range of wrist motion (Rainbow et al., 2015).

Extrinsic carpal ligaments

Extrinsic carpal ligaments are divided into three groups: palmar radiocarpal ligaments, palmar ulnocarpal ligaments, and dorsal radiocarpal ligaments (DRCs) (Fig. 13.36), (Pulos and Bozentka, 2015). Palmar ligaments are important in preventing both dorsal and palmar carpal translation than the dorsal ligaments. Katz et al. (2003) showed that the palmar structures provided a greater restraint to dorsal translation (61%) and palmar translation (48%) of the carpus than did the dorsal structures.

In general, the palmar ligaments limit excessive wrist extension, while the dorsal ligaments resist excessive flexion. The radial ligaments limit ulnar deviation and the ulnar ligaments limit radial deviation. Radiocarpal and ulnocarpal extrinsic ligaments restrict the axial rotation of the hand relative to the forearm and allow the proximal carpal row to maintain contact with the distal radius during wrist movements. The ligamentous attachment to the triquetrum resist to the tendency of the proximal carpal row to slide ulnarly due to the radial inclination of the distal radius.

Palmar extrinsic ligaments

Palmar extrinsic ligaments can be defined as two-ligamentous system, proximal and distal V system. The distal V system joins the radius to the triquetropisiform complex via the capitate; the proximal V system joins the radius to the ulnar styloid via the lunate and the triquetrum.

The distal V system: It is composed of the different ligaments connecting the lateral border of the radius to the capitate and the triquetropisiform complex. Scaphotrapezoid ligament, the arcuate ligament (deltoid ligament or triquetrocapitoscaphoid ligament), and the radioscaphocapitate ligament form the distal palmar V system. The main function of this system is to stabilize

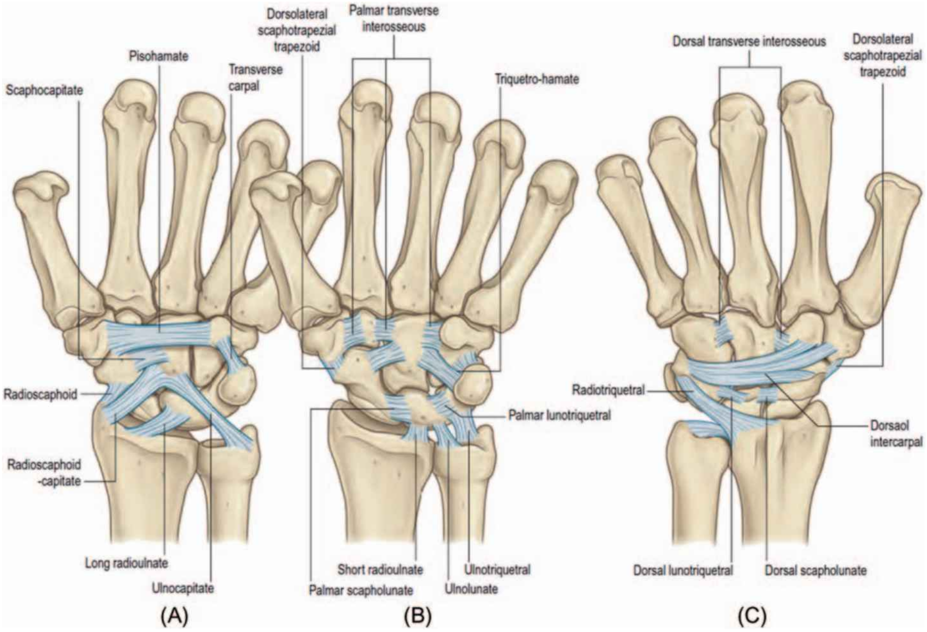


FIGURE 13.36 Palmar and dorsal wrist ligaments (Standring, 2016).

the scaphoid and the capitate. The deep and superficial systems merge at the pisiform. In fact, the flexor retinaculum also has ligamentous attachments extending to the pisiform.

The radioscaphocapitate ligament creates a sling from radial styloid to capitate (Fig. 13.37). This ligament has two components: the radioscaphoid ligament and the radiocapitate ligament. The radioscaphoid ligament [also known as the radial collateral ligament (RCL)] starts obliquely from the radial styloid and ends at the proximal side of the scaphoid tubercle (Fig. 13.37). The radiocapitate component of the radioscaphocapitate ligament arises from the scaphoid courses along the capitate. It plays a role in scaphoid stability since it resists the palmar flexion of the scaphoid. It becomes stretched during ulnar deviation and during extension with radial deviation of the distal carpal row. The ligament controls flexion of the scaphoid during radial deviation, and it works together with the radioscapholunate ligament to stabilize the proximal pole of the scaphoid (Mayfield, 1984; Berger and Landsmeer, 1990). Because of its mechanical importance it is preserved when doing proximal row carpectomy (PRC). It acts as a primary stabilizer of the wrist after PRC and prevents ulnar drift of the carpus. In the case of the proximal half of the scaphoid fractures, the radioscaphocapitate ligament can fold into the fracture gap. This may predispose the healing and lead to scaphoid pseudarthrosis.

Triquetrocapitoscaphoid ligament, which forms the ulnar side of the distal V system, extends from the palmar side of the triquetrum to the distal scaphoid. The ligament prevents flexion of the proximal carpal row. The STT ligament connects the scaphoid with the trapezium and the trapezoid.

The proximal V system: It is composed of the different ligaments connecting the radius, lunate and the TFCC. The radiocarpal ligaments including the long and short radiolunate ligaments together with the ulnolunate and ulnotriquetral ligaments form the proximal palmar V system. It prevents palmar subluxation, the natural tendency of the lunate. Deep fibers form the radioscapholunate ligament and ulnocarpal fibers that are part of the TFCC. These fibers are believed to enhance or stabilize intraarticular fibers. It also plays role in load transfer between the carpus and the ulna.

The long and short radiolunate controls the radial and ulnar deviation. The long radiolunate ligament (the radiolunotriquetral ligament) courses through lunate and triquetrum forming the radial leg of the proximal V system (Fig. 13.37). This ligament prevents ulnar translocation of the lunate. Vickers et al. suggested that abnormal radiolunate ligament contributes to a Madelung deformity. It is the strongest ligament of the wrist and prevents ulnar translation of the carpus along the radius, which has an ulnar inclination. It may also control the flexion of the scaphoid during radial deviation. The short radiolunate ligament has an effective role in stabilizing the lunate during excessive extension (Fig. 13.38), (Berger, 1997; Brown et al., 1998; Watson and Weinzweig, 2001).

Madelung deformity

The deformity is characterized by a prominent dorsal subluxation of the ulnar head and palmar sag of the hand and

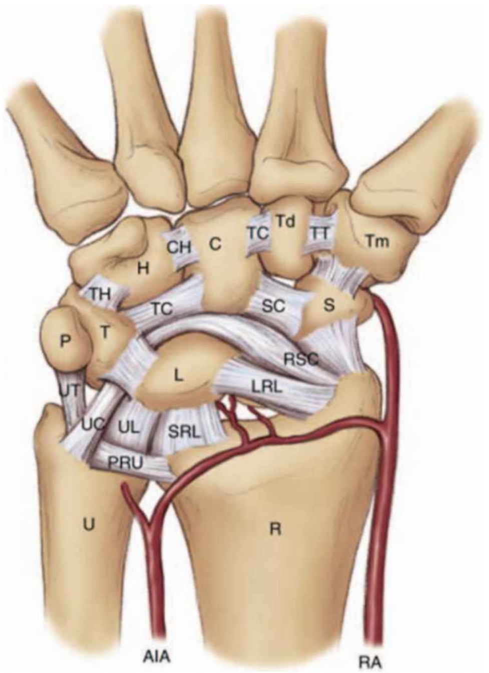


FIGURE 13.37 The extrinsic carpal ligaments include the RSC, LRL, radioscapholunate, and SRL ligaments on the radial carpus. The UL, UC, and UT ligaments form the volar ulnar ligamentous complex (Slutsky and Osterman, 2009). *LRL*, Long radiolunate ligament; *RSC*, radioscaphocapitate; *SRL*, short radiolunate ligament; *UL*, ulnolunate; *UC*, ulnolunocapitate; *UT*, ulnotriquetrocapitate.

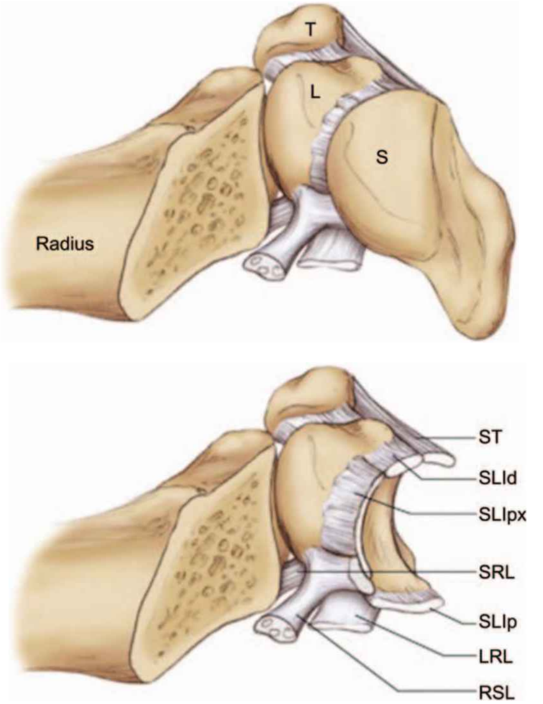


FIGURE 13.38 View of the volar radiocarpal ligaments from within the wrist. *L*, Lunate; *LRL*, long radiolunate ligament; *RSL*, radioscapholunate ligament (ligament of Testut); *S*, scaphoid; *SLId*, dorsal portion of scapholunate ligament; *SLIp*, palmar segment of scapholunate ligament; *SLIpx*, palmar and intermediate portion of scapholunate ligament; *SRL*, short radiolunate ligament; *ST*, scaphotriquetral ligament; *T*, triquetrum (Slutsky and Osterman, 2009).

*wrist with a shortened forearm (Fig. 13.9). Patients suffer from wrist pain and the aesthetic deformity. Vickers et al. found that there is an abnormal palmar ligament tethering the lunate to the palmar–ulnar radius epiphysis and metaphysis (Vickers' ligament) that is thought to contribute to the deformity (*Vickers and Nielsen, 1992*). de Brito et al. demonstrated abnormal ligament in four cases in which the patients underwent CT, CT arthrography and MRI. All cross-sectional imaging studies demonstrated the presence of an abnormal radiolunate ligament with radial insertion within a bony gutter (*de Brito et al., 2007*).*

Ulnolunate ligament and ulnotriquetral ligament form the ulnar leg of the proximal V, which are key components of the TFCC. The ulnolunate ligament arises from the anterior part of the TFCC, inserts on the lunate. The ulnotriquetral ligament is located between the TFCC and the proximal side of the triquetrum. These two ligaments form the ulnocarpal ligamentous complex with the superficial ulnocapitate ligament. This structure that is also an important component of the TFCC (Feipel and Rooze, 1999; Watson and Weinzweig, 2001), plays an active role in stabilizing the DRUJ. Lengths of the ligaments stabilizing the DRUJ change during forearm rotation. From neutral position to pronation the UC, UL, and UT ligaments shortened, whereas from neutral position to supination, the UT ligament lengthened but the radioscaphocapitate, UC, UL, and dorsal intercarpal ligaments (DICs) decreased (Chen and Tang, 2013). These ligaments stabilize the distal carpus and prevent nondissociative carpal instability.

Dorsal V system: Dorsal V ligament system consists of radiotriquetral and scaphotriquetral ligaments (Fig. 13.39). It is a transverse V-shaped ligamentous connection where its apex is located at the triquetrum. They are weaker than the palmar ligaments. The proximal leg of the V system connects the radius and triquetrum. The distal leg of the V connects the scaphoid and the triquetrum. The DIC arises from the scaphoid and ends in the trapezoideum and trapezium. The DIC ligament serve as a secondary stabilizer to the lunocapitate joint and controls lunate extension with the wrist in neutral position. The DIC ligaments are demonstrated to prevent carpal instability nondissociative with DISI following distal scaphoid excision. The DRC arises from the radius and ends at the triquetrum (Watson and Weinzweig, 2001). The radiotriquetral ligament is one of the dorsal ligaments that serve as a stabilizer of the ulnar column. In the case of its rupture in combination with the LTIL causes VISI deformity. The lunate is stabilized by the dorsal radiotriquetral ligament and the capitate is stabilized by the DICs. This

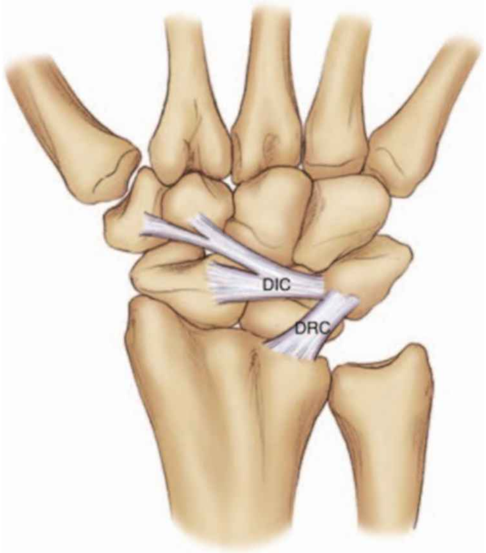


FIGURE 13.39 The DRC and DIC ligament complex (Slutsky and Osterman, 2009). *DIC*, dorsal intercarpal; *DRC*, dorsal radiocarpal.

ligamentous system prevents the carpus from sliding along the radial joint surface.

The effect of scaphoid excision on carpal kinematics

*After a distal scaphoid excision, most wrists develop a mild form of dorsal intercalated segment instability. Distal scaphoid excision leads to significant lunate extension through an imbalance in the force couple between the STT joint and the triquetrohamate joint. Because the DIC ligament serve as a secondary stabilizer to the lunocapitate joint and prevent further lunate extension, it is concluded that the development of a clinically symptomatic dorsal intercalated segment instability with lunocapitate subluxation after distal scaphoid excision may be due to an incompetent DIC ligament (*Kamal et al., 2012*).*

Intrinsic carpal ligaments

Intrinsic carpal ligaments originate from the carpal bones and insert to the carpal bones. There are numerous palmar, dorsal, and interosseous intercarpal ligaments connecting the carpal bones. The fibers run transversely between two carpal bones and run longitudinally between the radius and the scaphoid.

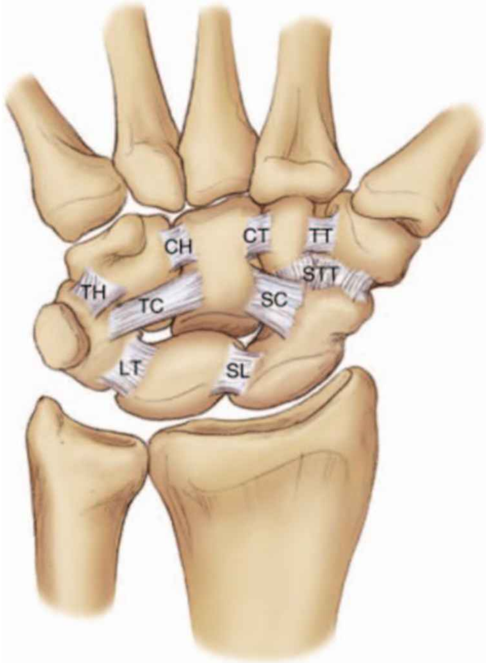


FIGURE 13.40 The intrinsic carpal ligaments. *CH*, capitohamate ligament; *CT*, capitotrapezoid ligament; *LT*, lunotriquetral ligament; *SC*, scaphocapitate ligament; *SL*, scapholunate ligament; *STT*, scaphotrapeziotrapezoid ligament; *TC*, triquetrocapitate ligament; *TH*, triquetrohamate ligament; *TT*, trapeziotrapezoid ligament (Slutsky and Osterman, 2009).

The interosseous ligaments between the distal carpal bones are short and strong with only a minimum of freedom of movement between the carpal bones (Fig. 13.40). Since the distal carpal row functions as a single unit, Taleisnik (1976) described this row as a functional monolith. Trapeziotrapezoid ligament and trapeziocapitate ligaments allow minimum movement between trapezium, trapezoid, and capitate. The hamatocapitate ligament (palmar, dorsal, and interosseous) provides the greatest movement between the capitate and the hamate providing the interaction of the proximal and the distal carpal rows. The radioscapholunate ligament (ligament of Testut and Kuentz) arises from the radius and inserts at the scaphoid and the lunate and the SLIL. It functions as a neurovascular bundle carrying the terminal brunches of the AIN.

The proximal interosseous ligaments, including SLIL and LTIL, are the ligaments with the most freedom of movement. The proximal carpal row is a semirigid modular functional unit and has an important role in carpal mechanism. The lunatum is the key bone of this row connected to the triquetrum by the LTIL and connected to the scaphoid by the SLIL. The SLIL controls the motion between the scaphoid and the lunate, which is essential for normal carpal kinematics. It is one of the most important ligaments in terms of its mechanical and proprioceptive functions. The semicircular morphology of the SLIL permits gliding and torsional movements of the scaphoid and the lunate against each other during wrist movements. The palmar fibers of the SLIL are long allowing greater mobility, whereas the dorsal fibers are short and thick. Disruption of the membranous and palmar portions of the SLL did not result in the development of an increased scapholunate gap. This may indicate a predynamic instability condition that is stabilized by the dorsal SLL, preventing the increase in the scapholunate gap. This may also support surgical treatment recommendations, which suggest that repair of the dorsal component only of the SLL will be effective (Patterson et al., 2013; Waters et al., 2016).

The lunotriquetral ligament is located between the lunatum and the triquetrum. The rotational movements between lunate and triquetrum are minimal. The LTIL allows the triquetrum to move distally during ulnar deviation (Ritt et al., 1998). The LTIL had a higher stiffness than the SLIL (Nikolopoulos et al., 2011). The axial stresses to the lunotriquetral space are lower than the scapholunate space, as the head of the capitate tends to move proximally between the scaphoid and the lunate concentrating the axial loads on the SLIL. Therefore the SLIL injuries are more common than the LTIL injuries.

Ulnocarpal complex (triangular fibrocartilage complex)

Ulnocarpal complex provides stabilization of the radius and ulna, stabilization of the lunatum, and load transfer to the ulnar side. Palmer and Werner (1981) divided the TFCC into five structures (Fig. 13.41):

1. medial (ulnar) collateral ligament (extends from ulnar styloid to the pisiform and the triquetrum. The posterior fibers are stronger than the anterior fibers),
2. triangular fibrocartilage (articular disk) and dorsal and palmar radioulnar ligaments (arises from the sigmoid fossa of the radius and inserts to the base of the ulna),
3. ulnocarpal meniscus (radiotriquetral ligament),
4. ulnolunate ligament (ulnar component of proximal V system), and
5. ECU tendon sheath.

The three-dimensional kinematic analysis revealed that palmar radioulnar ligaments were stretched during axial loading, suggesting that a tear of the palmer ligament can result from a fall on an outstretched hand leading to DRUJ instability (Hojo et al., 2019). Chen et al. (2016) investigated the length changes of the distal radioulnar ligament at different wrist positions, and it was found that the distal radioulnar ligament may be under great tension at the position of hyperextension with maximal pronation.

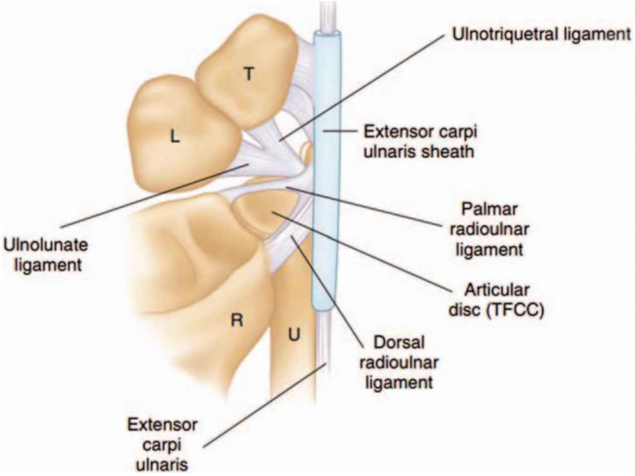


FIGURE 13.41 Ulnocarpal complex of the wrist (Magee et al., 2015).

Carpal kinematics

The carpus is arranged in two horizontal rows and three biomechanically organized vertical columns according to their spatial configuration. The horizontal rows are formed by the proximal carpal bones (scaphoid, lunate, triquetrum, and pisiform) and the distal carpal bones (hamate, capitate, trapezoid, and trapezium). Within the proximal row, each carpal bone has slight independent mobility. Mobility between the carpal bones of the distal row is small due to strong ligament attachments. According to Taleisnik (1976), the three vertical columns are divided into radial, ulnar, and central column. The radial column is formed by the scaphoid; the ulnar column is formed by the triquetrum and pisiform; and the central column is T-shaped, whereby the distal carpal row with the trapezium, trapezoid, capitate, and hamate is connected to the radius via the lunate. This allows two degrees of freedom with extension–flexion and radial–ulnar deviation. If the proximal and DRUJs are also taken into account, pronation and supination are also possible as a third degree of freedom. Circumduction is a circular movement of the hand on the forearm combining these wrist movements.

Global wrist motion

Global wrist motion is usually measured using the angle of the third metacarpal or the capitate with respect to the radius hence, there is little motion between the third metacarpal and the capitate (Patterson et al., 1997).

Radiocarpal and the midcarpal motion

Despite numerous studies, investigating the relative contribution of the radiocarpal and the midcarpal joints to global wrist motions; there is still confusion about the direction and magnitude of relative motion (RM) among carpal bones during wrist motion. There are important reasons for the disagreements, including small study populations and different measurement methods. Three-dimensional measurements of the carpal bones become available only recently (Rainbow et al., 2016).

Functional wrist range of motion

Many daily living activities (ADLs) require 45 degrees sagittal plane movements (5–10 degrees flexion, 30–35 degrees extension) and 20 degrees frontal plane movement (15 degrees ulnar deviation and 10 degrees radial deviation). Wrist extension and ulnar deviation movements are particularly important for gripping activities. Maximum flexion/extension or radial/ulnar deviation excursion occurs with the wrist in neural position with respect to the other plane of motion. Therefore neutral alignment should be maintained when performing range of motion (ROM) measurements. It is important to note that since the wrist normally functions in a diagonal plane (dart plane) that combining extension with radial deviation and flexion with ulnar deviation during common ADLs, assessment of wrist motion in the functional diagonal patterns need to be considered.

Wrist arthrodesis position

The wrist is positioned at approximately 10–15 degrees extension and 10 degrees ulnar deviation in for the wrist arthrodesis (Flowers and LaStayo, 2007).

Dart-throwing motion

The DTM is the plane of global wrist motion used during most ADLs. Along the dart-throwing plane, most of the motion occurs at the midcarpal joint while the proximal row remains still. Arthrodesis of the radiocarpal joint instead of the midcarpal joint will allow better wrist function during most ADLs by preserving the dart thrower's motion (Brigstocke et al., 2014). Following carpal ligament or distal radius injury or reconstruction, the goal is usually to minimize loading of the healing structures. Wrist motions in which scaphoid motion is minimal proposed to reduce length changes in associated ligamentous structures. Werner et al. determined that the scaphoid tuberosity excursion is minimal during dart-throwing motion. Therefore using dart-throwing motion during rehabilitation provides minimal changes in ligament loading while still allowing wrist motion (Werner et al., 2016). Nonetheless, when the scapholunate ligaments were torn, it was shown that the scaphoid shifted toward the radial styloid more than the lunate, inducing a scapholunate gap. Based on these findings, dart-throwing exercises after scapholunate ligament repair was not recommended unless the joint is stabilized with wires or screws (Garcia-Elias Serrallach et al., 2014).

Wrist movements are much more complex because of the RM of the carpal bones. The movements of the individual carpal bones and their contribution to overall wrist motion must be appreciated to understand the movement of the wrist. There are accepted concepts about carpal motion during wrist movements. Carpal bones perform three-dimentional motion, including flexion–extension, radial–ulnar deviation, and pronation–supination. Carpal motion is coordinated by the alignment of the joint surfaces and also by the control of the carpal ligaments. During the movements the distal carpal row is more rigid than the proximal row and the bones of the distal carpal row behave as a single, functional unit with little intercarpal motion and are directly linked to movement of the third metacarpal (Kobayashi et al., 1997a,b). The distal row bones relatively tightly connected to each other; however, the proximal row is loosely bound to one another (44) allowing greater amount of motion during wrist movements. Therefore the proximal row is proposed to function as an intercalated segment between the distal row and the radius (Ruby et al., 1988). The scaphoid, lunate, and triquetrum exhibit significant "out of plane" motion, noted mainly in relation to the distal row bones (Kobayashi et al., 1997a,b; Stoesser et al., 2017).

The extent of the movement of the scaphoid, the lunate, and the triquetrum is greater than the other carpal bones. During wrist flexion and extension, they flex relative to radius and during wrist extension and ulnar deviation they extend (Berger, 1996; Werner et al., 1997). These motions occur in the same plane with the global wrist motion. The scaphoid, lunate, and triquetrum do not function as a single unit, but each bone has a unique arc of motion during global wrist motion (Werner et al., 1997). The characteristics of the motions differ among the proximal carpal bones. The scaphoid and the lunate show different magnitude and speed characteristics of motion during wrist movements. The scaphoid move greater and faster than the lunate resulting in relative flexion between the scaphoid and lunate during wrist flexion and relative extension during wrist extension (Kobayashi et al., 1997a, b; Stoesser et al., 2017). However, during wrist movements, carpal bones also produce motions that occur in a plane different from the global wrist motions, which are known as out-of-plane motions. During wrist flexion the scaphoid and triquetrum undergo pronation with respect to the lunate, and supination during wrist extension (Kobayashi et al., 1997a,b).

Central column, including the joints between the radius–lunate–capitate—third metacarpal, is important for the sagittal plane movements (flexion–extension). The wrist flexion and extension occurs with the synchronous movement of the convex–concave relationship of the radiocarpal and midcarpal joints (Fig. 13.42). There are conflicting results of the contributions of the proximal and distal carpal rows to global wrist movements due to the different study groups and measurement techniques. Studies usually use capitate to represent the relative contribution of the distal carpal row (therefore, the midcarpal joint) and the lunate to represent the relative contribution of the proximal carpal row (therefore, the radiocarpal joint). Some studies report that the capitate moves greater than any other carpal bones in the proximal row resulting in greater contribution of the midcarpal joint to both

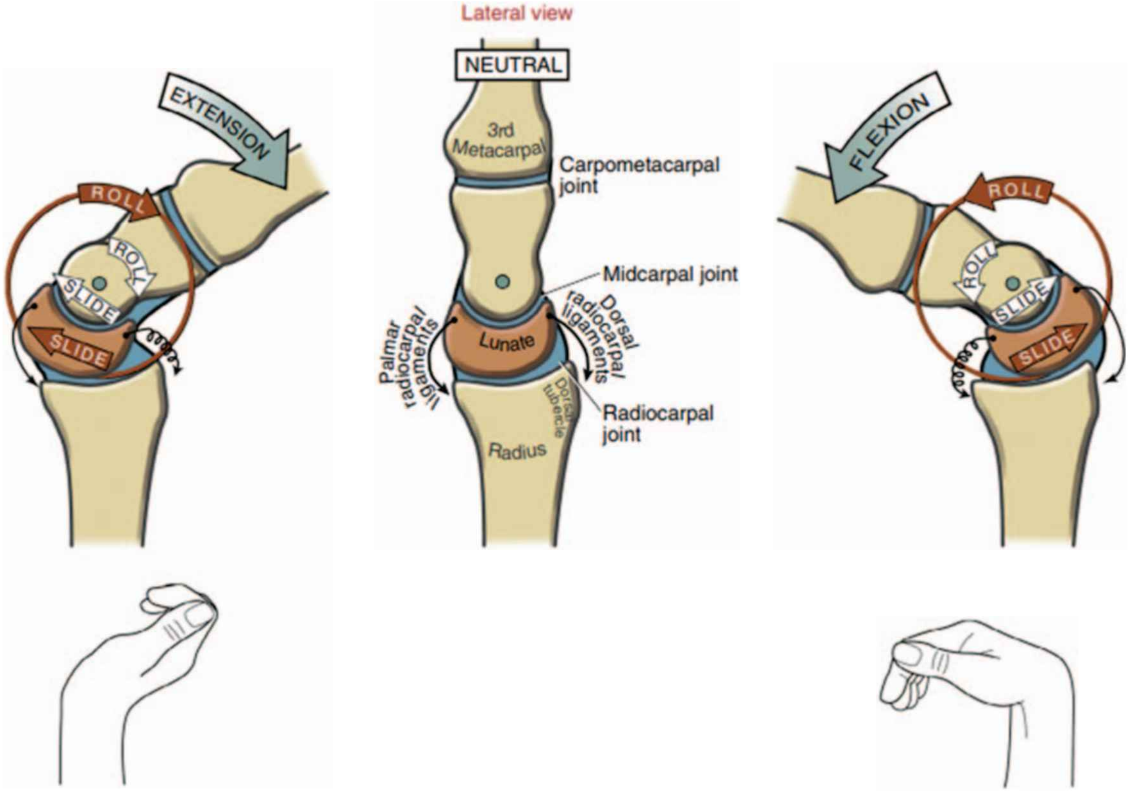


FIGURE 13.42 Arthrokinematics of wrist flexion and extension (Mansfield and Neumann, 2014).

flexion and extension (Werner et al., 1997; Camus et al., 2004). Some studies report that the contribution of the midcarpal joint to wrist flexion is about 60%–70% (Sarrafian et al., 1977; Kobayashi et al., 1997a,b). However, other studies report equal or greater relative contribution of the radiocarpal joint than the midcarpal joint to wrist flexion (Stoesser et al., 2017). Similarly, studies reveal different results about the contribution of the radiocarpal and the midcarpal joints to global wrist extension. While some studies demonstrate the greatest the contribution of the midcarpal joint to extension of the wrist (Sun et al., 2000), the others report the opposite findings (Sarrafian et al., 1977). However, there is still no consensus about the relative contributions of the proximal and the distal carpal rows to movement of the wrist, it is important to understand that global wrist motion requires movements at both the radiocarpal and the midcarpal joint. Furthermore, the amount of carpal rotations was proportional to global wrist rotations (Fraysse et al., 2014).

Kawashima et al. hypothesized that wrist joint motion involves a "wrist rhythm" similar to the scapulohumeral rhythm. The ratio of radiolunate and capitolunate joint motions during wrist joint motion was evaluated by dynamic radiography. Their findings indicated that the ratio of the radiolunate and capitolunate angle motions was approximately 1:4 during palmar flexion and approximately 2:1 during dorsiflexion (Kawashima et al., 2014). During global wrist motion the radiulunate joint contributes more motion in flexion and less motion in extension than the capitolunate joint. Capitolunate angles range from 16.9 degrees extension to 29.5 degrees flexion with a total ROM of 46.4 degrees. Radiolunate angles ranged from 12.2 degrees extension to 58.3 degrees flexion with a total ROM of 70.5 degrees.

Flexion and extension

During wrist extension the capitohamate and SC ligaments tighten with the increase of the tension of the flexor retinaculum. Capitate and carpal ligaments play a key role in load transfer during wrist movements (39). During loading the scaphoid rotates radially in the vertical plane and the proximal part of the scaphoid is stabilized between the radius and the capitate. Since there is no ligament support between the capitate and the lunate, the capitate is pushed from dorsal to volar by the lunate (39). Triquetrum follows the lunate motion. Lunate and triquetrum are not stable enough for load transmission; therefore the scaphoid is loaded greater than the other carpal bones at certain positions (39). In a study investigating load transfers in the wrist extension position stated that the forces focus on two

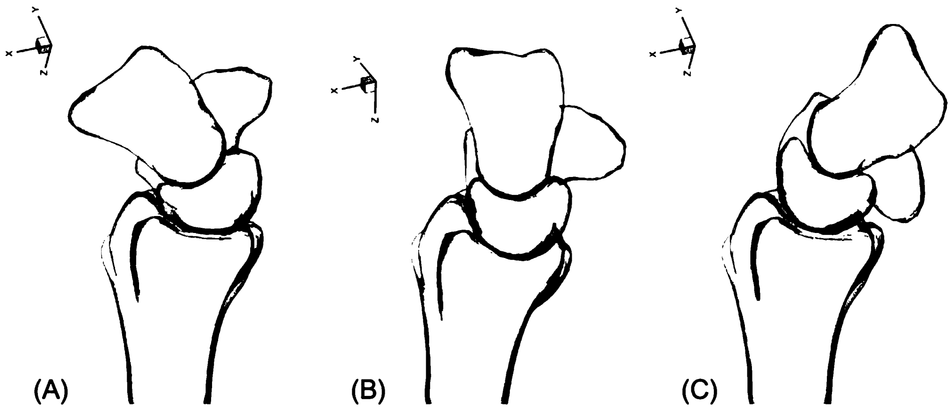


FIGURE 13.43 Carpal motions during flexion and extension. The radius, scaphoid, lunate, and capitate are shown with the wrist in (A) extension, (B) neutral, and (C) flexion. In flexion, wrist motion is shared more equally between the midcarpal and radiocarpal with respect to the radius. In extension, wrist motion is primarily radiocarpal (Kaufmann et al., 2006).

parts of the scaphoid, one of which is the proximal pole and the other is the distal pole (39).

The arthrokinematics of wrist flexion is similar to the extension movement (Fig. 13.43). While the wrist is moving to flexion, the lunate moves dorsally on the radius. Capitate moves dorsally like the lunate. This movement in the midcarpal joint is much less than in the radiocarpal joint. The wrist joint is not stable in the full flexion position (12).

Perilunate dislocations

*Considering the relationship of the intercarpal ligaments in wrist extension position, the volar LT ligament is significantly tensioned during movement. The load transmitted from the capitate to the dorsal corner of the lunate pushes the lunate in the volar direction. Therefore perilunate dislocations are seen rather than lunate fractures after high-energy trauma (*Tolat et al., 1992*).*

During flexion and extension of the wrist the scaphoid and lunate follow the motion of capitate (Fig. 13.44). During wrist flexion the scaphoid flexes and pronates slightly, while during wrist extension, the scaphoid extends and supinates (Foumani et al., 2009). The lunate basically shows the same movements as the scaphoid but to a lesser degree. Although scaphoid and lunate follow the capitate during the flexion and extension, the scaphoid follows the capitate rotations more closely the lunate lags behind allowing some intercarpal motion between the scaphoid and lunate (Foumani et al., 2009). Because of the different size and curvature of the scaphoid and lunate, two bones move at different speeds on the radius during wrist movements. Moreover, the amount of the scaphoid motion is greater than the lunate. The differential displacement between the scaphoid and the lunate is controlled and minimized by the SLIL. Therefore the large magnitude of differential rotation between the scaphoid and lunate is proposed to be responsible for the high incidence of scapholunate ligament injuries (Stoesser et al., 2017).

Carpal tunnel pressure

*Active pinch or power grip increase the carpal tunnel pressure particularly in motions, including extension. Modification of wrist motion during intensive occupational tasks is important to prevent median nerve compression due to elevated carpal tunnel pressure (*McGorry et al., 2014*).*

Carpal motions during wrist movements

Some investigators concluded that wrist kinematics could not be readily simplified into such a two-linkage system comprising the proximal and distal rows. Patterson et al. (1998) determined that the capitate rotation axis is not fixed around a stationary axis, thus the translation of the carpal bones should be accounted when considering wrist motions. Wolfe et al. proposed that the scaphoid should not be considered part of the proximal carpal row because it acts as an independent bone with kinematics that are dependent not only on its neighboring bones but also on the direction and magnitude of wrist motion. They demonstrated that there is a substantial intercarpal motion between the scaphoid and lunate, along with the out-of-plane motions, exhibited among these three bones (Wolfe et al., 1997, 2000). Similarly, Werner et al. studied the individual contributions of the scaphoid, capitate, lunate, and triquetrum to different wrist motions using an in vitro wrist motion simulator. They demonstrated that the scaphoid and lunate do not contribute equally to a 60 degree arc of wrist flexion and extension and concluded that the scaphoid and lunate do not normally function as a unit (Werner et al., 1997).

Using implanted staples and orthoradiography Ruby et al. (1988) documented 24 degrees of motion between the scaphoid and lunate during global flexion and extension. Radiolunate motion was found to represent 41% of radiocapitate extension and 56% of radiocapitate flexion. Moojen et al. investigated the kinematics of carpal bones using CT scan. They reported that contributions of the scaphoid and lunate to 60 degrees of wrist extension were

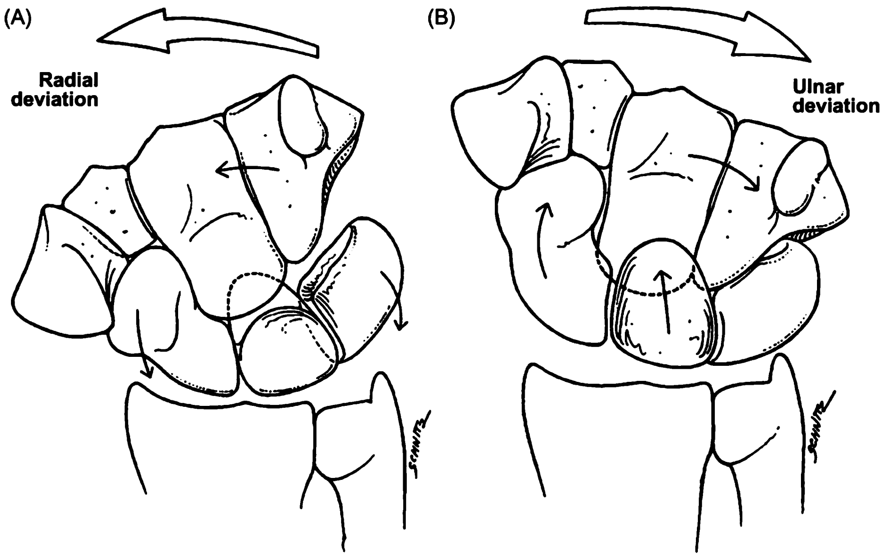


FIGURE 13.44 (A) High position during radial deviation and (B) low position during ulnar deviation (Wolfe, 2001).

87% and 66%, respectively (Moojen et al., 2002). Wolfe et al. determined the three-dimensional kinematics of the capitate, scaphoid, and lunate relative to the radius. In flexion the scaphoid contributed 73% of capitate motion and the lunate contributed 46%. In extension the scaphoid contributed 99% of capitate motion and the lunate contributed 68% (Wolfe et al., 2000). Kobayashi et al. demonstrated that radiolunate motion comprised 50% of wrist extension but only 36% of wrist flexion. Scapholunate motion measured 22 degrees extension and 16 degrees flexion (Kobayashi et al., 1997a,b).

Radial and ulnar deviation

The arthrokinematics of radial and ulnar deviation movements is more complicated than flexion–extension movements. During radio–ulnar deviation the proximal and the distal rows showed dissimilar rotation patterns (Fig. 13.44). Generally, radial and ulnar deviations were dominated by midcarpal motion since the carpal bones of the distal row followed the global wrist motion during the deviations. The radiocarpal and midcarpal joints are equally contributed to ulnar deviation, whereas midcarpal joint contributes more motion to radial deviation (12). The out-of-plane motions of the carpal bones are more complex during radial and ulnar deviation of the wrist. Radial deviation is accompanied by relative flexion and pronation of the proximal carpal row, whereas ulnar deviation is accompanied by relative extension and supination of the proximal carpal row (Kobayashi et al., 1997a,b; Camus et al., 2004). The distal carpal row demonstrates the reverse of out-of-plane motions of the proximal carpal row (Foumani et al., 2009). Unlike the flexion and extension of the wrist, during radio–ulnar deviation, the scaphoid and lunate moved together with negligible intercarpal motions between the two bones (Fig. 13.45), (Ruby et al., 1988; Short et al., 1997; Foumani et al., 2009). Radial deviation compresses STT joint decreasing the distance between the trapezium and the radial styloid, which then forces the scaphoid into flexion. The hamate disengages from the triquetrum and two bones separate. During ulnar deviation the proximal row glides on the radial and TFCC surfaces. The scaphoid rotates in the dorsal direction increasing its proximal to distal height. The triquetrum migrates distally along the hamate. The hamate engages against the triquetrum. The compressive force of the hamate toward the triquetrum pushes the proximal carpal bones toward the radial styloid (Fig. 13.44). This compression force helps to stabilize the wrist in activities requiring strong grip force. At the last point of ulnar deviation, the triquetrum contacts with the TFCC.

Loading pattern of each carpal bone during wrist movements was determined using a finite element wrist model. Minimum loads were carried by triquetrum during flexion, radial, and ulnar deviation while minimum loads were carried by capitate in extension. Maximum loads were carried by trapezium in neutral and ulnar deviation and flexion but by scaphoid in radial deviation and extension (Oflaz and Gunal, 2019).

Column and row wrists

Two situations known as column wrists and row wrists differently combine flexion/extension and radial/ulnar deviations of the proximal row. In the column wrists, flexion/extension movement of the proximal row prevails on the radioulnar deviation. This type of wrists is seen in patients with hyperlaxity. On the contrary, subjects with row wrists show no flexion or extension of the proximal row. This type of wrists refers to rigid wrists (Craigen and Stanley, 1995).

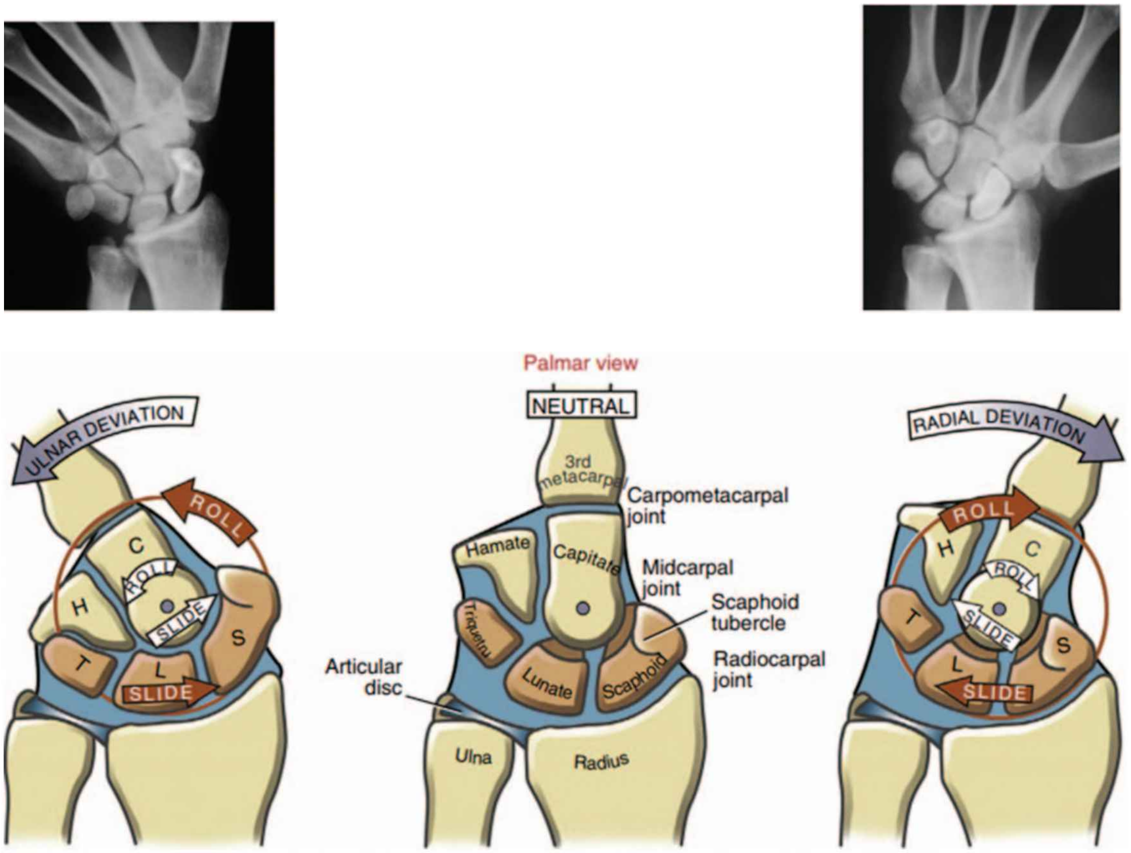


FIGURE 13.45 Arthrokinematics of the wrist during radial and ulnar deviation (Neumann, 2010).

Muscles

Extrinsic extensor muscles

The extensor tendons at the level of the wrist form six extensor compartments as they pass under the extensor retinaculum that are designated by Roman numerals from lateral to medial (Table 13.1). These compartments prevent bowstringing of the extensor tendons.

Proprioceptive function of the ligaments

Mechanoreceptors mapped in the wrist ligaments exhibited different innervation patterns with regard to their distribution in the ligaments, their receptor density, and ligaments' structural composition (Petrie et al., 1997; Hagert et al., 2005, 2007; Lin et al., 2006). Innervation patterns of the wrist ligaments suggest that they have different functional roles. The dorsal and triquetral ligaments contain more mechanoreceptors than the radiovolar ligaments, which indicate the critical role they play in the sensorimotor function of the wrist joint (Hagert et al., 2005, 2007). All ligaments connecting the scaphoid to the adjacent carpal bones provide proprioceptive information; however, the most richly innervated ligament is the SLIL (Hagert et al., 2007). The SLIL is innervated from terminal branches of the PIN and, through the radioscapholunate ligament, AIN (Fig. 13.35). The primary sensory nerve ending found in the SLIL is the Ruffini ending (Hagert et al., 2004), which signals during excessive joint positions and rotation, which is when the ligament is at risk of being torn. Innervated ligaments are able to initiate inhibitory and excitatory muscular activity via ligamento-muscular reflexes. These reflexes stabilize the excessive stress in the ligaments through synergistic muscle activation relevant to the joints (Hagert et al., 2004).

Wrist extensor muscles

There are three primary wrist extensor muscles, including the extensor carpi radialis longus (ECRL), extensor carpi radialis brevis (ECRB), and extensor carpi ulnaris (ECU). The EDC, EPL, EİP, and extensor digiti minimi (EDM) are the secondary wrist extensors.

Extensor carpi radialis longus and brevis muscles

The ECRL muscle is one of the powerful wrist extensors with the ECRB muscle. It also provides radial deviation to the wrist. The muscle arises distal to the brachioradialis muscle from the lateral supracondylar ridge of the humerus and the lateral epicondyle of the humerus.

TABLE 13.1 The compartments and functions of the extensor tendons.

Compartment	Tendons	Function	Innervation
First	Extensor pollicis brevis	Extends the thumb MCP joint	PIN
	Abductor pollicis longus	Extends the thumb CMC joint	PIN
Second	Extensor carpi radialis longus	Extends and radially deviates the wrist	Radial nerve
	Extensor carpi radialis brevis	Extends the wrist	Radial nerve
Third	Extensor pollicis longus	Extends the thumb IP joint	PIN
Fourth	Extensor digitorum communis	Extends the 2–4 fingers	PIN
	Extensor indicis proprius	Independently extends the index finger	PIN
Fifth	Extensor digiti minimi	Independently extends the small finger	PIN
Sixth	Extensor carpi ulnaris	Ulnarly deviates and extends the wrist	PIN

CMC, Carpometacarpal; *IP*, interphalangeal; *MCP*, metacarpophalangeal; *PIN*, posterior interosseous nerve.

It courses in the superficial muscle layer and inserts on the dorsal base of the second metacarpal. Since the ECRL muscle takes its origin at the supracondylar ridge of the humerus about 4–5 cm proximal to the epicondyle, it plays a role in elbow flexion. Its role in wrist extension is greater when the elbow is extended.

The ECRB muscle originates from the lateral epicondyle, the RCL, and the annular ligament of the radius. It also courses in the superficial muscle layer and inserts on the dorsal base of the third metacarpal. As it is more centrally located, it causes more direct wrist extension, which makes the ECRB a more likely choice for tendon transfers to extend the wrist. Three wrist extensors have very different moment arms of extension. While the ECRB is the most effective extensor of the wrist, the ECU is the weakest wrist extensor.

Extensor carpi ulnaris muscle

This muscle is located on the ulnar aspect of the forearm. It arises from the lateral epicondyle of the distal humerus, courses along the dorsoulnar forearm, and inserts at the pisiform bone, the pisometacarpal ligament, and at the base of the fifth metacarpal. It crosses the wrist at the level of the ulnar and passes through the sixth extensor compartment lying within a bony groove on the dorsal surface of the ulna. An extension of the dorsal retinaculum and a subsheath lying deep in the retinaculum maintain the ECU tendon within this groove. The tendon compartment, tendon sheath, and the tendon itself are firmly attached to the TFCC and are thus part of the whole structure. The structural integrity of this ulnar part is important for normal wrist mechanics. It is the strongest wrist ulnar deviator. The ECU tendon rotates around the ulnar head. Therefore the ECU muscle contributes to wrist extension depending on the forearm position. When the forearm is in full supination, the ECU tendon is situated in a dorsal position relative to axis of flexion/extension motion, resulting in a greater contribution to wrist extension. When the forearm is pronated, its tendon lies on the ulnar side of the styloid process, which diminishes the extension torque by 60% and primarily causes ulnar deviation. This positional variation impacts its function and its relative stability. In forearm supination the tendon exits the sixth compartment at an angle of approximately 30 degrees. Tension on the ECU retinaculum and subsheath is therefore greater during activities involving forearm supination. It decelerates supination via the palmar radioulnar ligament and limits the radial deviation. It is also involved in regulating force transmission through hand via the TFCC (Campbell et al., 2013).

Wrist flexor muscles

Flexor carpi ulnaris muscle

The FCU muscle is the most medial muscle of the superficial flexors of the forearm. It arises with two heads; humeral and ulnar head. The humeral head originates from the medial epicondyle of the humerus and the antebrachial fascia. The larger ulnar head originates from the dorsal aspect of the olecranon and the proximal two-thirds of the posterior border of the ulna. The muscle inserts primarily into the pisiform, but also it has attachments to the hook of hamate and palmar base of the fifth metacarpal. It is the strongest wrist flexor and works with the FCR muscle. It also contributes to ulnar deviation with the involvement of the ECU and EDC muscles. During strong grip, it has an important role in stabilizing the carpus. The FCU also assists in stabilizing the pisiform; therefore indirectly assist the abductor digiti minimi muscle to abduct the small finger that has its origin at the pisiform. The FCU muscle has a larger physiologic cross-sectional area and has shorter fiber length. Thus the FCU muscle is designed for more force production than for excursion compared with the FCR.

Flexor carpi radialis muscle

The FCR muscle originates from the common flexor origin of the medial epicondyle of the humerus. It is the more radially located muscles of the superficial flexors of the forearm [along with the pronator teres, palmaris longus (PL), FDS, and FCU]. The muscle courses distally and radially to the wrist. The tendon passes radial to the carpal tunnel and travels through its own fibro-osseous tunnel formed by a narrow bony groove below the tubercule of trapezium. The FCR tendon often has a synovial sheath in the distal portion of its course. The muscle inserts palmar to the base of the second metacarpal. A small slip of the tendon inserts at the third metacarpal and at the trapezial tuberosity. The FCR mainly performs flexion in the wrist and stabilizes the carpus. During strong wrist flexion, it works with the FCU and finger flexors. During radial deviation by the ECRL the FCR assists with radial deviation of the wrist. From the architectural standpoint, the FCR has a moderate fiber length and physiologic cross-sectional area which indicates that it is designed for both excursion and force production. However, the relatively longer fiber length indicates that the FCR is designed more for excursion compared with the FCU.

Palmaris longus muscle

The PL is one of the central muscles of the superficial flexors of the forearm. The PL muscle is one of the most variable muscles in terms of presence, muscle variations, and anomalies. It is documented that the PL is no longer present in around 12.8% of the population. It arises from the medial epicondyle and courses between the FCU and FCR muscles. The PL muscle is a weak flexor of the wrist. It also assists to forearm pronation with a weak contribution. It is clinically important as it is usually used as a free tendon grafts.

Kinesiology in various carpal conditions

Carpal kinematics following distal radius fracture

The radiocarpal joint made a greater contribution to wrist motion than the midcarpal joint in flexion, and the midcarpal joint made a greater contribution to motion than the radiocarpal joint in wrist extension. Increasing dorsal angulation caused increased radiocarpal joint contribution to the total wrist motion, with the effect being more pronounced in wrist flexion. Conversely, increased dorsal angulation resulted in decreased midcarpal joint motion throughout the motion arc, particularly, in wrist extension. Dorsal angulation resulted in increased lunate flexion with respect to the distal radius. Even a mild dorsal angulation may affect ligament mechanics; the need for surgical correction in patients with malunion with mild dorsal angulation after a distal radius fracture is controversial. Chen et al. (2015) investigated in vivo changes in the lengths of carpal ligaments in mild-degree dorsal angulation following a distal radial fracture. It was found that while the DRC and ulnotriquetral ligament were substantially lengthened, the long radiolunate ligament was substantially shortened at most wrist positions except extension. The contact areas of the DRUJ and the contact area on sigmoid notch are also altered in patients with malunited distal radius fractures. The in vivo findings suggest that the centroids of the contact area on sigmoid notch move volarly during wrist flexion—extension and ulnar deviation (Xing et al., 2015). The contact area of the DRUJ increases during wrist flexion and decreases during wrist extension and ulnar deviation.

Carpal kinematics following scapholunate instability

The scapholunate ligament injuries are the most frequent intercarpal ligamentous injuries. SLIL injuries lead to carpal instability, progressing toward a scapholunate advanced collapse wrist. The injury typically occurs from a trauma in hyperextension/radial deviation, most often because of a fall onto an outstretched hand. In these conditions the scaphoid is under two opposite constraints, toward the extension because of the wrist extension and toward the flexion because of the combined radial deviation. When the scapholunate ligament is injured, the scaphoid goes to flexion because of longitudinal forces and the lunate goes to extension because of the triquetrum. The scapholunate gap increases, creating a scapholunate diastasis. These biomechanical changes lead to a decrease of the carpus height, as the scaphoid and lunate reduce their functioning distance. This causes the extrinsic ligamentous system to become slack and the passive stability of the carpus to be compromised.

Studies showed that after scapholunate ligament injury, the scaphoid showed an increase in translational deviation in wrist motions and the movement of the lunate is impaired, especially in radial—ulnar deviation (Eschweiler et al., 2016; Stromps et al., 2018). Omori et al. investigated in vivo three-dimensional patterns of dorsal intercalated segment instability deformity resulting from scapholunate dissociation. They found that in the scapholunate dissociated wrists, the scaphoid rotates in the direction of flexion and pronation and translated dorsally and radially. The lunate was extended and supinated. The capitate, trapezoid, and trapezium translated dorsally. Contact area of the radioscaphoid joint shifted dorsoradially owing to dorsoradial subluxation of the scaphoid proximal pole. The congruity of the radiolunate, lunocapitate, and STT joints was preserved. In the malunion cases, incongruity of the radioscaphoid joint became more pronounced as the scaphoid and distal carpal row translated more dorsally along dorsal angulation of the distal radius (Omori et al., 2013).

Dimitris et al. examined the force across SLIL during wrist movements, and it was found that the average recorded maximal tensile force across the scapholunate joint during all tested motions was 20 N. Thus the surgical methods for the scapholunate repair should be strong enough to provide better outcomes for patients (Dimitris et al., 2015). Daly et al. determined the contact pressures between the scaphoid and the lunate and the distal radius during push-up positions before and following SLIL sectioning in a cadaver study. A push-up with the wrist in extension causes a significant increase in the pressure in the radioscaphoid fossa. This finding may help explain why degenerative arthritis first develops in the radioscaphoid fossa before involving the radiolunate fossa. Sectioning the SLIL caused the centroid of pressure in the radioscaphoid fossa to move an average 1.4 mm radially. This finding could provide a possible explanation for the development of radioscaphoid arthritis occurring before radiolunate arthritis (Daly et al., 2018).

Carpal kinematics following carpal arthrodesis

Carpal fusions are useful for treating specific carpal disorders to reduce pain and instability and to maximize wrist motion and strength. The surgeon selects the appropriate treatment by considering the degree of stability, the chronicity of the injury, functional demands of the patient, and former patient's outcomes as well. All arthrodesis treatment should consider changes on the load transmission, and also bones' fusion rates and pain reduction on patient's outcomes. The load distributions following carpal fusions were analyzed in many studies. Florez et al. analyzed the load distribution through the wrist joint with an arthrodesis treatment. They found that arthrodesis for treating SLAC/SNAC II-III reduced the load transmitted through the radioscaphoid fossa by 8% confirming the treatment objective. Alternative treatments that reduce load distribution on the radiocarpal joint should be three corner and capitolunate arthrodesis for treating SLAC/SNAC-II; and for SLAC/SNAC-III four corners with scaphoid excision. On Kienböck's disease SC arthrodesis is more effective on reducing the load transmission through the radiolunate and ulnolunate joints (Marquez-Florez et al., 2016). Got et al. analyzed the wrist motions in cadaveric wrists in the intact state and after undergoing either a four-corner fusion or two- and three-bone fusion. Four-corner fusion leads to decreased wrist flexion, whereas the two- and three-bone fusions demonstrate increased radial deviation and pure flexion. Radial extension and pure extension were decreased in all types of fusions (Got et al., 2016). It was also suggested that the load transmission through the ligaments varied by the type of the fusion. The loads carried by the ligaments following limited carpal fusion are recorded in a finite element study with simulating four types of limited carpal fusions (STT, capitohamate, four-corner fusion with and without scaphoid excision). Radioscaphoid and long radiolunate ligaments carried significantly more loads if not excised during the surgery (Bicen et al., 2015).

Radioscapholunate (RSL) fusion has been utilized for treatment of radiocarpal arthritis for patients with an intact midcarpal joint. This preserves midcarpal joint motion while alleviating pain. A cadaveric study was designed to measure and compare the ROM of the human wrist before and after an RSL fusion, followed by distal scaphoid excision, and finally excision of the triquetrum. It was found that ROM of the simulated RSL fusion with distal scaphoidectomy is improved with excising the triquetrum, through an increase in ulnar deviation. Therefore RSL fusion with distal scaphoidectomy and triquetrectomy is recommended as an alternative to total wrist arthrodesis for patients with an intact midcarpal joint (Bain et al., 2014). However, RSL arthrodesis results in increased midcarpal contact pressures that may help to explain the incidence of midcarpal arthritis. Excision of the distal scaphoid further increases contact pressures in the remaining midcarpal joint. Surgeons should consider these alterations in contact characteristics of the midcarpal joint when excising the distal scaphoid for improved range of motion (Holleran et al., 2013).

Kinesiology of the Hand

Introduction

The hand is one of the most complex organization serves as a sensory organ which generates a fine motor response. Since the somatosensory homunculus depends on the amount of the sensory receptors, the hand has a large representation in the sensory cortex (Fig. 13.46).

The hand has important roles in hygiene, heat regulation, emotional expressions, and social communication. The sophisticated function of the hand depends on the functioning of various supporting structures, including 19 bones, 19 joints, 29 muscles, 3 peripheral nerves, and its vascular system (Figs. 13.47 and 13.48).

Three movement axes of the hand enable the positioning of the hand in space. There is a delicate relationship

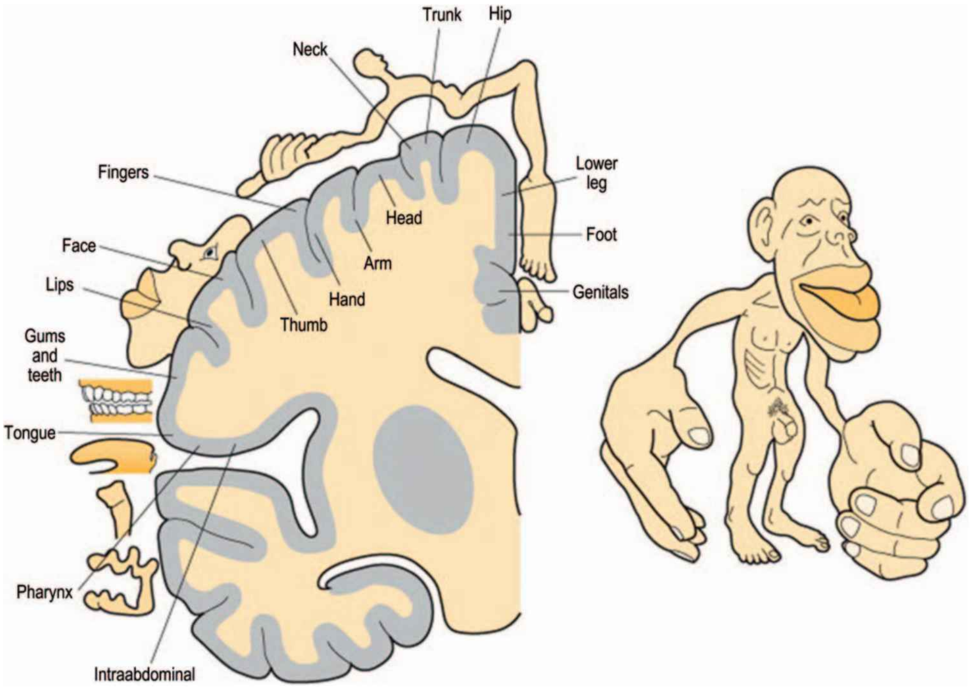


FIGURE 13.46 Homuncular organization of the primary SI cortex in a coronal section at the level of the postcentral gyrus (Michael-Titus et al., 2010). *SI*, Somatosensory.

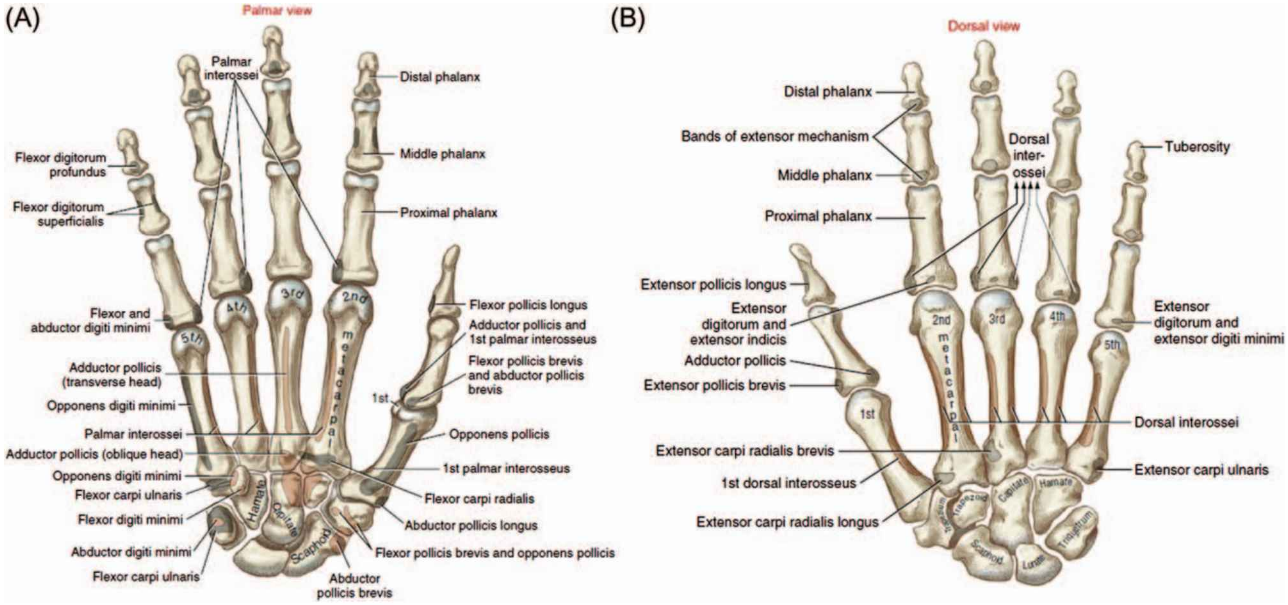


FIGURE 13.47 Anatomy of the hand: (A) palmar view of the bones of the right wrist and hand and (b) dorsal view of the right wrist and hand. Proximal attachments of muscle are indicated in red and distal attachments in gray (Neumann, 2010).

between the length, mobility, and position of each finger in the hand. The relative length relationship between the fingers becomes important during the grasp and release activities. The length disadvantages of the metacarpals on the ulnar side are compensated by the increased mobility of the flexion–extension movement at the fourth and fifth CMC joints. Therefore fourth and fifth digits on the ulnar side can move more obliquely during grip activities (Fig. 13.49), and they especially play a role in strong grip.

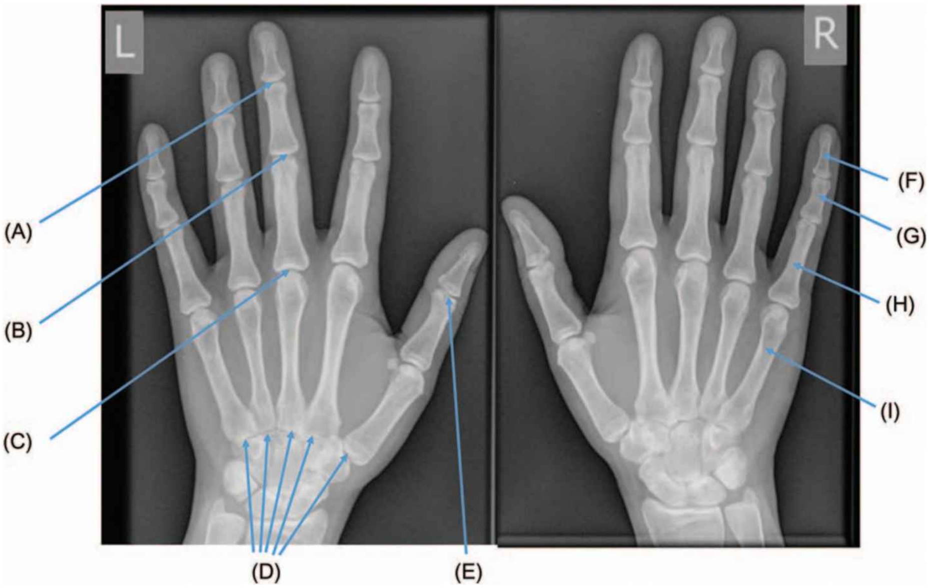


FIGURE 13.48 Normal anteroposterior radiograph of both hands. (A) Distal interphalangeal joint, (B) proximal interphalangeal joint, (C) metacarpophalangeal joint, (D) carpometacarpal joints, (E) interphalangeal joint, (F) distal phalanx, (G) middle phalanx, (H) proximal phalanx, and (I) metacarpal (Williams et al., 2019).

Osteology

Metacarpals

The five metacarpal bones are short tubular bones of various lengths. The morphology of each metacarpal is generally similar among all of the digits. Each metacarpal consists of a proximal end (base), a shaft, and a distal end (head). The bases have small articular facets for articulation with adjacent metacarpal bones. The morphology of the proximal bases of the second through the fifth metacarpal is varied among the five digits (Fig. 13.50). The bases of the metacarpals of the second and third fingers have slightly flattened facets, whereas the articular facet of the fourth finger is slightly more curved, and the fifth finger has a saddle-shaped facet. Each metacarpal articulates with the corresponding carpal bone(s) (Raoul Tubiana and Mackin, 1998; Neumann, 2003; Kisner et al., 2006; Oatis, 2009; Hirt et al., 2017; Hirth et al., 2017). As its dorsal part is wider than the palmar part, it allows stable articulations with the distal carpal row.

The variations in the bases of the metacarpal bones affect the mobility of their CMC articulations. The second and third CMC articulations present almost no motion, which is why these are considered to be the stable columns of the palm, while the fourth and fifth articulations are quite mobile. The first metacarpal bone has a saddle-shaped articular surface. It is the most mobile metacarpal bone allowing the opposition motion at the thumb.

The convex metacarpal heads are round from volar to dorsal covered by the articular cartilage. They are more curved than the bases of phalanges to which they articulate. The longitudinal axes of the second and third metacarpals are directed toward the scaphoid because the second and third metacarpal heads are pronated with respect to their base. The axis of the fourth and fifth metacarpals is directed toward the lunate since the fourth and fifth metacarpal heads are supinated with respect to their base (Fig. 13.51).

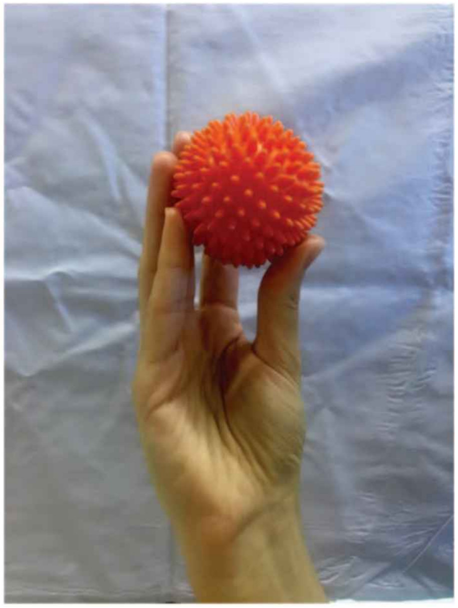


FIGURE 13.49 Oblique orientation of the fourth and fifth digits during grip.

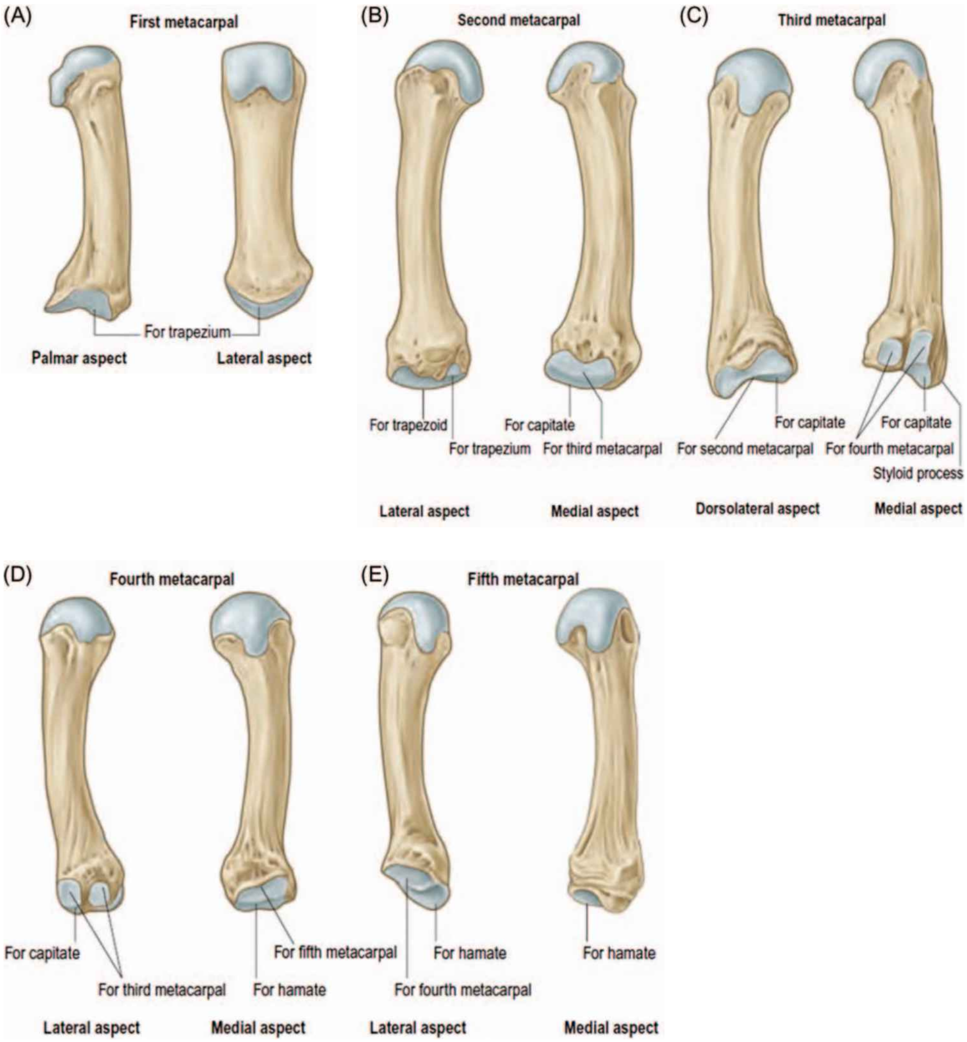


FIGURE 13.50 Anatomy of the metacarpal bones (Standring, 2016).

The articular surfaces of the metacarpal heads are asymmetrical. The dorsal extension of the articular cartilage allows small amount of hyperextension at the MCP joints. The articular surfaces are more variable in the radioulnar direction, which influences the amount of ulnar and radial deviation that can occur at each of the MCP joints. The head of the metacarpal of the thumb is quite variable allowing a wide range of motion at this joint. It is flatter and broader in the radioulnar direction than those of the other metacarpals, which reduces the radioulnar motion available at the thumb's MCP joint.

Phalanges

The hand has 14 phalanges; each finger has 3 phalanxes, which are referred to as proximal, middle, and distal (Fig. 13.52). The thumb has only a proximal and a distal phalanx. All phalanxes within each digit have similar morphology except for differences in size. The phalanges decrease in size from proximal to distal.

Phalanxes have bases, heads, and shafts (Fig. 13.53). The proximal, middle, and distal phalanges have a concave base, shaft, and convex head. However, the articulating surfaces of the bases of the phalanges are slightly flatter than the articular surfaces of the heads of the adjacent phalanx, the articulating surface of each base of the middle and distal phalanges is well adjusted to the articulating head of the respective phalanx. The heads of the proximal and middle phalanges are convex in a dorsovolar direction characterized by a trochlear shape, which limits the radioulnar movement at the joints (Raoul Tubiana and Mackin, 1998; Neumann, 2003; Kisner et al., 2006; Oatis, 2009; Hirt et al., 2017; Hirth et al., 2017). The two condyles of the proximal phalanx are slightly asymmetrical, whereas the condyles of the heads of the middle phalanges are more symmetrical. The distal phalanx of each digit has a concave base with a rounded tuberosity at its distal end. The tuberosity provides an anchor for the fingernails.

Artrology

Carpometacarpal joints

Carpometacarpal joints of the second–fifth digits

The CMC joints are located between the distal carpal row and the metacarpal bones (Fig. 13.54). Each metacarpal and its associated phalanges make up a ray of the hand. The CMC joints are enclosed by a single joint capsule. The respective articular surfaces are covered with articular cartilage. The mobility of the CMC joints increases from radial to ulnar sides of the hand as the articular surfaces become more curved. There are five CMC joints. The first CMC joint is located between the trapezium and the base of the first metacarpal. The second CMC joint is located between the trapezoid and the base of the second metacarpal. The third CMC joint is located between the capitate and the base of the third metacarpal. The fourth CMC joint is located between the hamate and the base of the fourth metacarpal. The fifth CMC joint is located between the hamate and the base of the fifth metacarpal.

The second and the third CMC joint have a plane type joint structure. These joints have relative rigidity, since they form the stable central column of the hand (Fig. 13.55). The metacarpal of the index finger articulates with the trapezium, trapezoid, capitate, and metacarpal of the long finger. It is the most stable of all CMC articulations. The first, fifth, and fourth CMC joints have a saddle type joint structure, which provides a relative mobility to the joints (Fig. 13.54). The fourth and fifth CMC joints contribute significantly to hand mobility (El-Shennawy et al., 2001; Nakamura et al., 2001; Nanno et al., 2007).

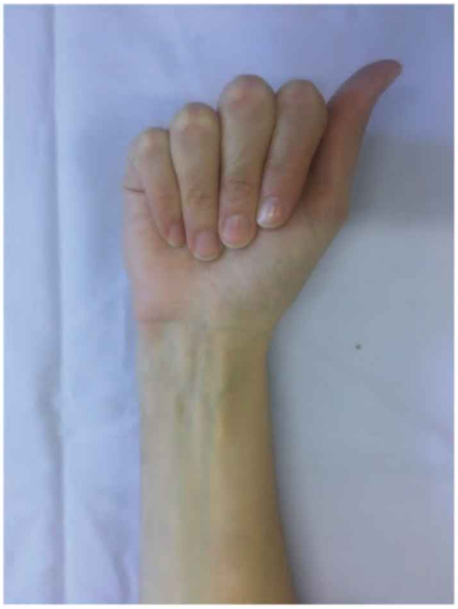


FIGURE 13.51 Normal alignment of the fingers.

The role of stabile and mobile columns in grip activities

The first, fourth, and fifth CMC joints allow the radial and ulnar side of the hand to move toward the center of the hand. This deepens the palmar concavity by increasing the distal transverse arch of the hand and allows a better grasping activity. Ulnar mobility involves the flexion of the fourth and fifth metacarpals and a slight rotation toward the third finger. The flexion of the fourth metacarpal is about 10 degrees and of the fifth metacarpal is about 20–25 degrees. The mobility of the ulnar side of the hand can be observed during strong grip (Fig. 13.56). The first CMC joint of the thumb is the most mobile, allowing the thumb to move toward the center of the palm allowing the thumb to oppose the other fingers. Conversely, relatively rigid second and third CMC joints provide a stable column for pinch activities.

The CMC joints are surrounded with an articular capsule. The capsule sends extensions distally between the adjacent metacarpals creating the intermetacarpal joints of the digits. The CMC and intermetacarpal joints are

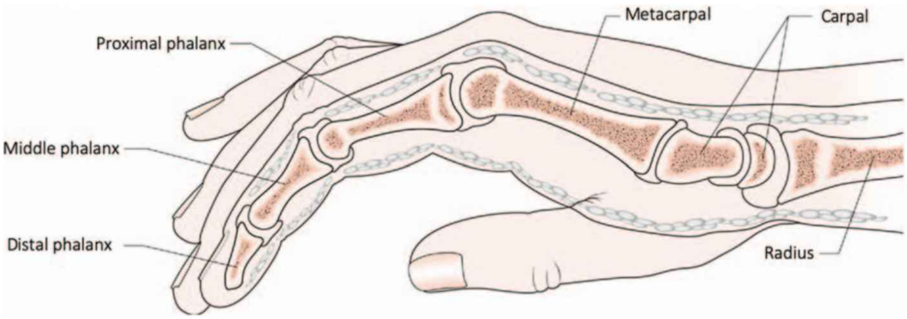


FIGURE 13.52 Sagittal view showing proximal, middle, and distal phalanges (Sambrook et al., 2010).

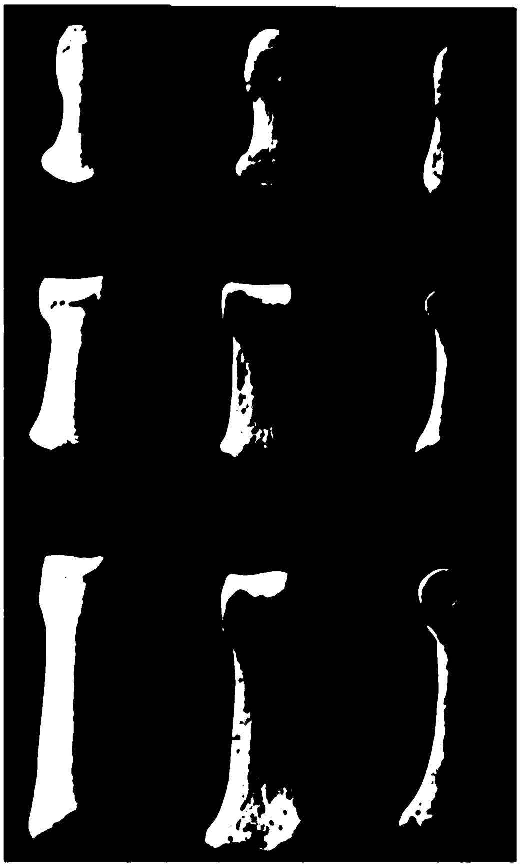


FIGURE 13.53 Anatomy of the phalanges. Dorsal (posterior), palmar (anterior), and lateral views shown, respectively (White and Folkens, 2005).

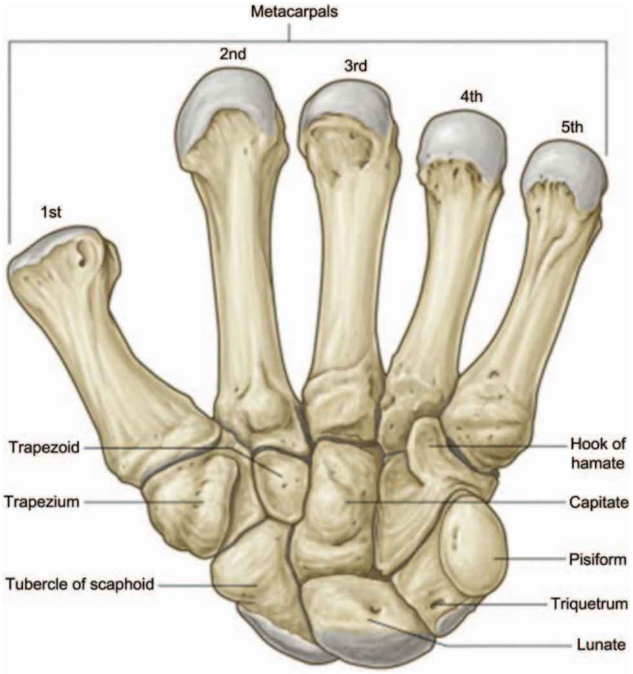


FIGURE 13.54 The CMC joints of the second–fifth fingers (Ombregt, 2013). *CMC*, Carpometacarpal.

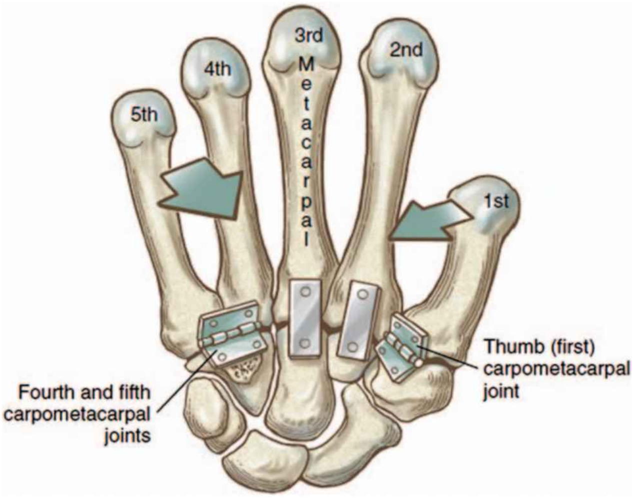

3rd
Metacarpal
2nd
4th
5th
1st
Thumb (first) carpometacarpal joint
Fourth and fifth carpometacarpal joints

FIGURE 13.55 The stable and mobile columns of the hand (Neumann, 2003).

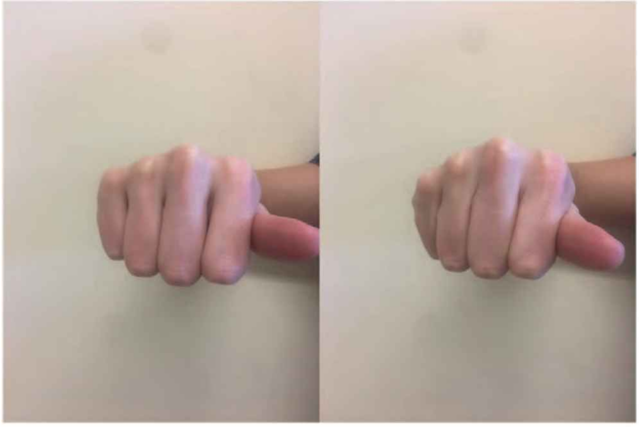


FIGURE 13.56 Mobility of the fourth and fifth CMC joints can be observed during strong grip. *CMC*, Carpometacarpal.

covered by dorsal and palmar intermetacarpal and interosseous ligaments.

Second–fifth carpometacarpal joint motion

The second through fifth CMC joints are synovial ellipsoidal joints primarily allowing flexion and extension. The fifth CMC joints also allow some abduction/adduction and rotation. This enables the fifth finger to make opposition toward other fingers (El-Shennawy et al., 2001; Nakamura et al., 2001; Nanno et al., 2007).

Carpometacarpal joint of the thumb

The CMC joint (trapeziometacarpal joint or basal joint) of the thumb is located between the first metacarpal and the trapezium. It is a saddle-shaped synovial joint (also described as ball-and-socket joint or as a condyloid joint) that allows for a wide range of motion of the thumb

(Fig. 13.57). The CMC joint has a unique function of opposition.

The trapezium and the metacarpal are positioned out of the plane of the hand turning slightly toward the fifth finger, which facilitates opposition of the thumb (Fig. 13.58).

Distribution of the forces on the joints of the thumb

Biomechanical studies showed that for a pinch force of 1 kg transmitted to the IP joint as 3.68 kg; to the MCP joint as 6.61 kg and to the CMC joint as 13.42 kg (Cooney and Chao, 1977). The standard grip force required to perform the ADLs independently is at least 9.9 kg and the pinch grip force is between 2.3 and 3.2 kg. Therefore the amount of force acting on the first CMC during the day can reach up to 40 kg. The act of the pinch forces throughout the day may be a predisposing factor for CMC joint degeneration and may increase the severity of CMC OA symptoms.

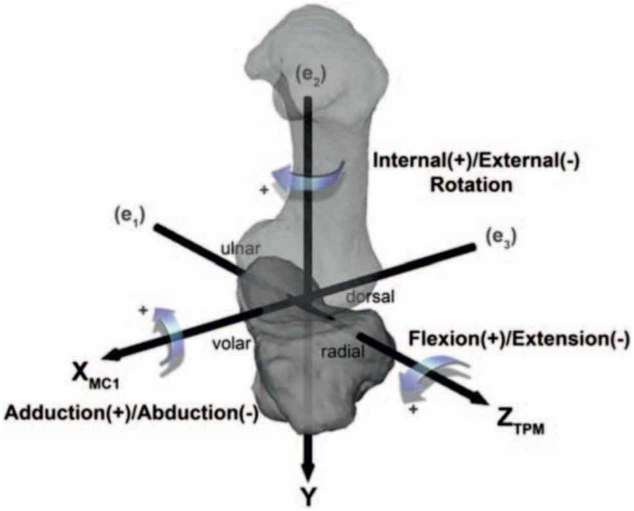


FIGURE 13.57 The saddle-shaped CMC joint of the thumb (Halilaj et al., 2013). *CMC*, Carpometacarpal.

The saddle joint of the thumb allows several major movements: flexion, extension, abduction, adduction, rotation, opposition, and reposition (Fig. 13.59).

The joint has two primary movement axes: the radioulnar axis (flexion–extension) and the dorsopalmar axis (abduction–adduction) (Fig. 13.60). Flexion and extension occur within the frontal plane. The thumb metacarpal moves in the plane of the palm toward (flexion) and away (extension) from the ulnar side of the hand. Abduction and adduction occur within the sagittal plane. The thumb moves in a perpendicular plane to the palm. The movement of the thumb away from the palm is described as abduction and toward the palm is described as adduction. Medial rotation (pronation) is the rotation of the pulp of the thumb toward the palm, and lateral rotation (supination) is the rotation of the pulp away from the pulp of the other fingers. Medial rotation of the first CMC joint occurs in conjunction with either flexion or abduction, while lateral rotation occurs with extension or adduction.

Opposition and reposition of the thumb are the combination of motions. Opposition is defined as simultaneous flexion, abduction, and medial rotation of the CMC joint.

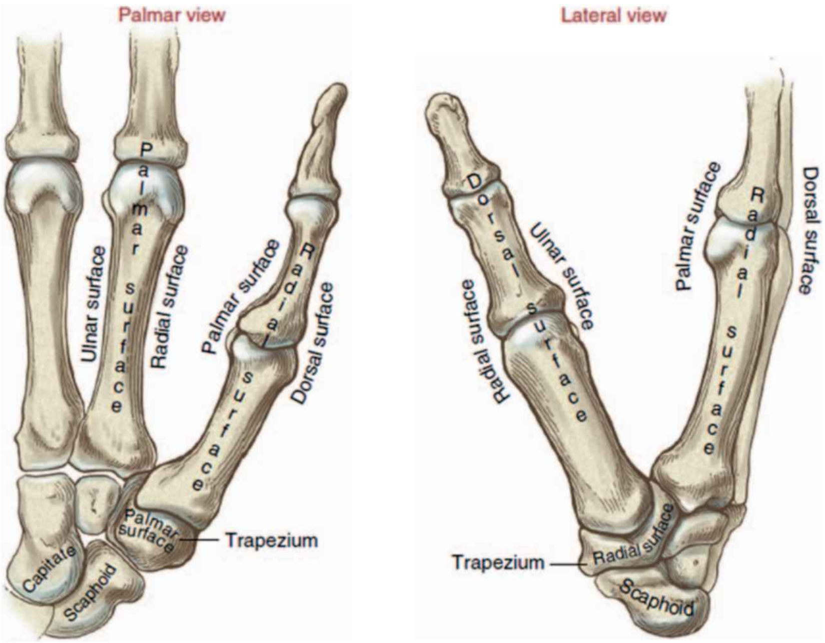


FIGURE 13.58 The CMC joint is positioned out of the plane of the hand (Mansfield and Neumann, 2014). *CMC*, Carpometacarpal.

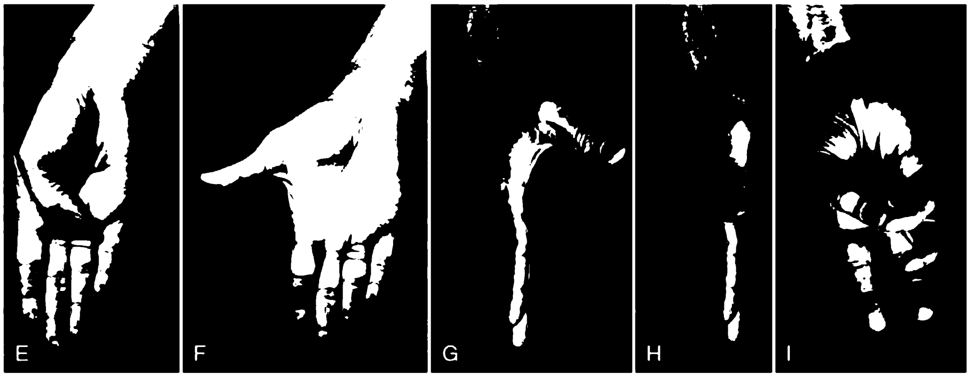


FIGURE 13.59 The movements of the thumb (Mansfield and Neumann, 2014).

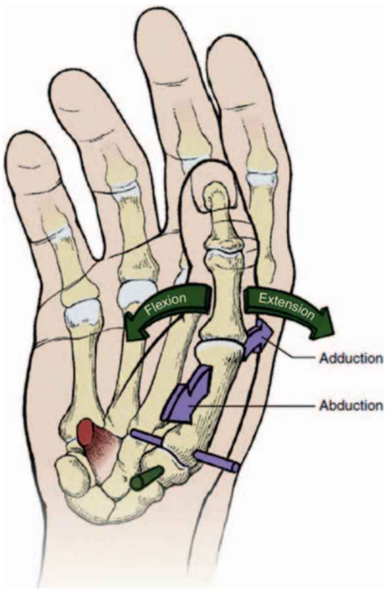


FIGURE 13.60 The radioulnar axis (flexion–extension) and the dorsopalmar axis (abduction–adduction) of the thumb CMC joint (Mansfield and Neumann, 2014). *CMC*, Carpometacarpal.

The movement of the opposition consists of two phases, including abduction phase and flexion phase. In the first phase the first metacarpal abducts and then in the second phase flexes and medially rotates toward the fifth finger. The thumb performs about 45–60 degrees medial rotation during full opposition. However, rotation movement occurs not only in the CMC joint but also in the MCP and IP joints. Reposition is a combination of adduction, extension, and lateral rotation of the metacarpal. The thumb is perpendicular to the palmar plane of the hand during adduction–abduction movements; it moves in parallel with the palmar plane during flexion–extension movements.

The motion limits of the CMC joint are 53 ± 11 degrees for flexion–extension; 42 ± 4 degrees for adduction–abduction; 53–60 degrees for opposition, and 17–21 degrees for axial rotation (Cooney et al., 1981, Goubier et al., 2009). The first CMC joint can make 10–15 degrees hyperextension from the anatomical position (Cooney et al., 1981).

The osteoarthritis of the carpometacarpal joint of the thumb

*The osteoarthritis of the CMC (CMC OA) joint of the thumb is characterized by progressive deterioration of joint surfaces. In Europe and the United States the prevalence of CMC OA is 30%–40% in postmenopausal women; in the general population it is reported to be in the range of 8%–12% (*Pellegrini et al., 1994; Cooley et al., 2003*). The change in CMC joint involves complex interaction of biochemical and biomechanical factors (*Haara et al., 2004*). Large compression and shear forces acting on the joint surface contribute to hyaline cartilage degeneration in a biochemical environment. CMC OA demonstrated the loss of the glycosaminoglycan from the extracellular matrix. CMC OA can be produced by both intrinsic and posttraumatic factors. Intrinsic factors include local and systemic factors. Local intrinsic factors include discrepancy between the joint surfaces and ligament laxity, whereas systemic intrinsic factors include gender, age, hypermobility syndrome, and ligament laxity due to hormonal changes. Posttraumatic factors such as Bennett fractures, CMC and MCP joint subluxations, and ligament injuries can lead to CMC OA (*Cauley et al., 1993*).*

First carpometacarpal joint kinematics

When the CMC joint of the thumb is in the neutral position, the axes of the first metacarpal and the trapezium are in the same direction. In this position the thumb is about 40 degrees abduction, 50 degrees flexion, and 80 degrees pronation, which makes it possible to position the thumb against the other fingers for grip activities. Therefore CMC joint of the thumb provides a quite wide range of motion to the first finger compared to other fingers.

Abduction and adduction kinematics of the first carpometacarpal joint

Abduction is the anterior movement that brings the thumb to a 90 degrees perpendicular position, pointing straight out from the palm in the sagittal plane. With the abduction movement, large concavity is provided to grasp the large objects. Abduction and adduction arthrokinematics of the CMC joint is based on the movement of the convex joint surface of the first metacarpal on the concave articular surface of the trapezium. During the abduction the convex joint surface of the metacarpal is rounded to the palmar side on the concave surface of the trapezium and slides to the dorsal side. Primary muscle responsible for this action is the abductor pollicis longus (APL) (Neumann, 2003). Full abduction movement causes AdP muscle, AOL, and intermetacarpal ligaments (IML) to stretch, which leads to pronation in the thumb. Abduction arthrokinematics of the joint resembles a cowboy falling forward on the saddle of the horse. As the cowboy falls forward (in the direction of abduction), a point on his chest rolls to anterior and the one in his back slides to posterior (Neumann, 2003). Adduction is the approximation of the thumb from the abduction position to the palmar side of the second finger. In full adduction the thumb is in the plane of the hand. The arthrokinematics of the adduction movement is the opposite of abduction arthrokinematics.

Flexion–extension kinematics of the first carpometacarpal joint

In the flexion movement the thumb moves from the palm toward the frontal axis. The flexion and extension movements of the CMC joint are associated with varying amounts of axial rotation of the metacarpal. The first metacarpal makes pronation during flexion and supination during extension due to the effect of the stretching ligaments. Axial rotation is not considered as a separate movement because it does not occur independently of other movements. The flexion and extension of the CMC joint is based on the arthrokinematics, where the concave joint surface of the metacarpal moves over the convex (transverse) surface of the trapezium. During the flexion the concave surface of the metacarpal rolls and slides in the ulnar (medial) direction (Imaeda et al., 1994). With full flexion, RCL is stretched and AOL becomes slack (Zancolli et al., 1987). During thumb extension the concave surface of the metacarpal slides and rolls in the radial direction along the transverse diameter of the joint. The groove in the joint surface of the trapezium directs the metacarpal to supination (Cooney et al., 1981). With the arthrokinematics of the extension movement, a cowboy falling sideways on the horse saddle can be compared to each other. As the cowboy falls sideways (toward extension), the points on his chest and back are "rolls and slides" to the same side (Neumann, 2003). With the full extension movement, ligaments located on the ulnar side of the CMC joint such as AOL are stretched.

Opposition kinematics of the first carpometacarpal joint

Opposition movement is supposed to be an indicator of a high level of functionality of the thumb and the hand. As the trapezium has a 45 degree angle in the sagittal plane compared to the other carpal bones, the web space between the first and second metacarpals and the unique configuration of the CMC joint allow for the movement of the thumb (Li and Tang, 2007). Opposition is a combination of the other primary movements already described for the CMC joint. It is described as a combined action of the APB, FPB, and OP muscles. Cooney stated that the action was performed by abduction, flexion, abduction of the CMC and the MCP joints (Cooney et al., 1981). According to Steindler, the action takes place in three phases. First, the extension performed by the extensor pollicis brevis and longus (EPB–EPL); second, abduction by the APB and APL; the third is flexion and pronation by the OP and FPB (Fig. 13.61), (MacConaill and Basmajian, 1977). The posterior oblique ligament (POL) is stretched during opposition. The CMC joint of the fifth finger indirectly contributes to the action. While the thumb is in full position, only half of the joint surfaces are in contact. For this reason, opposition movement during fine grip activities causes the forces passing through the CMC joint to turn into potential damaging stresses. Reposition is the movement of the thumb to return to the anatomical position from the position of the thumb and includes the adduction, extension, and supination movements of the thumb metacarpal. Reposition is performed by activation of the APL, EPL, and EPB muscles.

Measurement of the thumb opposition

The Kapanji index is used to assess the opposition of the thumb. It is a useful and practical tool based on the ability of the patient to touch their fingertips with the tip of their thumb (Fig. 13.62). A score of 0 indicates no opposition and a score of 10 indicates maximal opposition (Kapandji, 1986).

Ligaments of the first carpometacarpal joint

Joint stabilization is maintained by the joint capsule, ligamentous system, and dynamic muscle contraction. The joint is surrounded by five ligaments [anterior oblique (volar beak), ulnar collateral, first intermetacarpal, posterior oblique, and RCLs] (Table 13.2). There are two IML connecting the proximal ends of the metacarpals of the thumb and index fingers. These ligaments are important

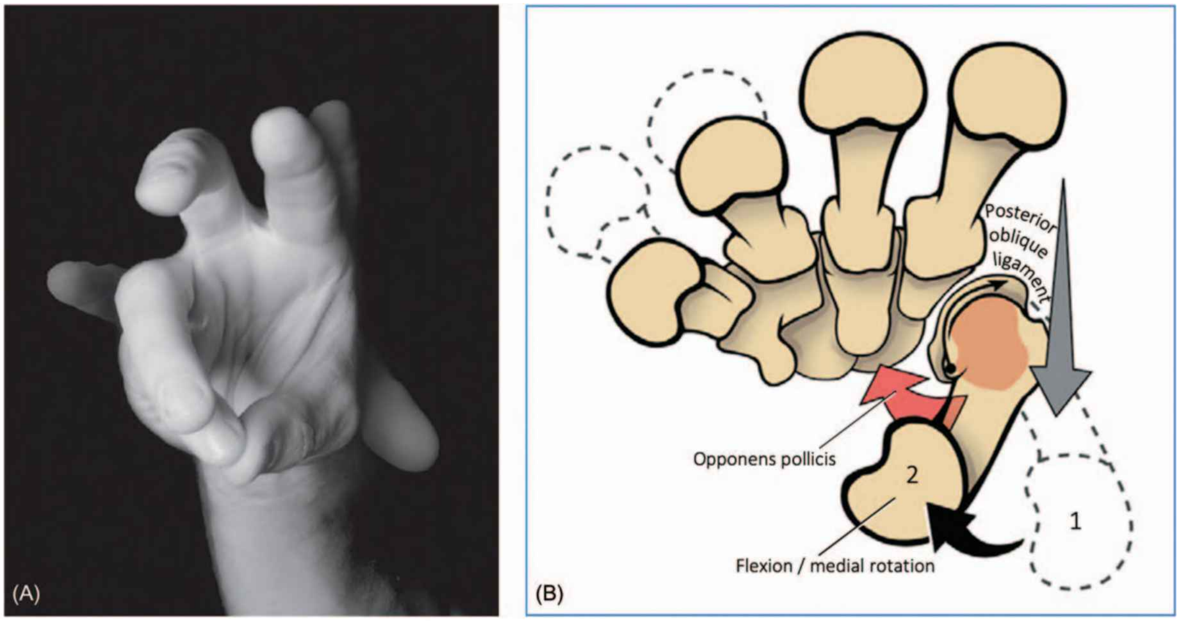


FIGURE 13.61 (A) Phases of opposition include thumb abduction, flexion and pronation; (B) When the opponens pollicis is contracted posterior oblique ligament is stretched. (Mansfield and Neumann, 2014).

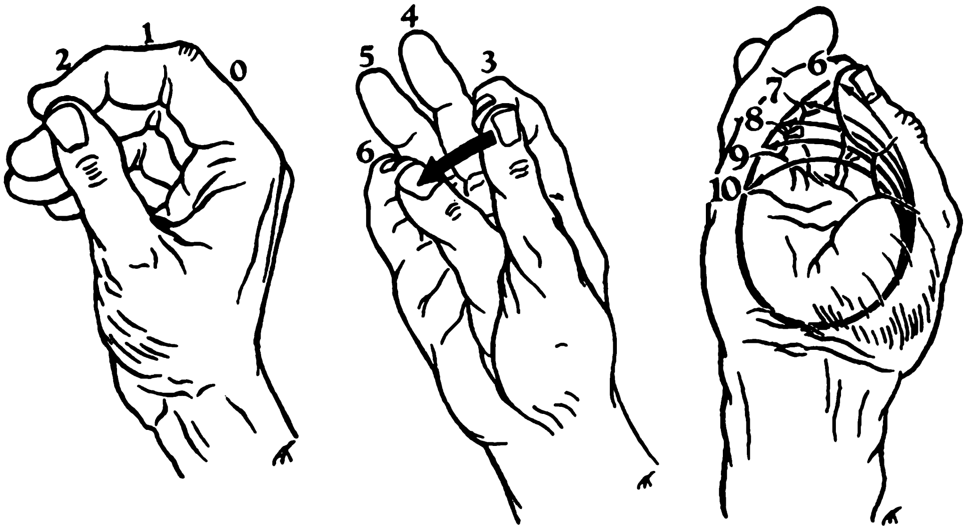


FIGURE 13.62 The Kapandji index for the assessment of the thumb opposition (Kapandji, 1992).

stabilizers of the thumb and prevent dislocation of the joint during movements. With the weakening of these ligaments after osteoarthritis, the first metacarpal tends to translate in dorsoradial direction (Bettinger et al., 1999; Leversedge, 2008).

Gamekeeper's thumb

*The ulnar collateral ligament (UCL) is the primary stabilizer of the thumb MCP joint against the valgus forces (*Fig. 13.63*). Injury to the UCL is a common ligament injury of the hand occurs with a fall onto the abducted thumb. However, it is usually referred to as "gamekeeper's thumb" and "skier's thumb," two terms refer different entities. The gamekeeper's thumb refers to a chronic injury to the UCL, whereas skier's thumb refers to an acute ligament injury as seen in athletes, particularly skiers, who fall onto the abducted thumb. The valgus stress test is established to diagnose the UCL rupture. The complete tear is diagnosed when the proximal phalanx is angulated radially by 30–35 degrees on the first metacarpal. Angulation of >15 degrees on stress testing compared with the contralateral thumb MCP joint*

TABLE 13.2 Ligamentous system of the carpometacarpal joint.

Ligament	Origo	Insertion	Elongated position
Anterior oblique ligament	Palmar tubercule of the trapezium	Palmar base of the metacarpal	Abduction, extension, opposition
Dorsoradial ligament	Radial surface of the trapezium	Dorsal surface of the metacarpal	All thumb motions except extension
Posterior oblique ligament	Posterior surface of the trapezium	Palmar–ulnar base of the metacarpal	Abduction, opposition
Ulnar collateral ligament	Transvers carpal ligament	Palmar–ulnar surface of the metacarpal	Abduction, extension, opposition
Intermetacarpal ligament	Dorsoradial surface of the second metacarpal	Palmar–ulnar base of the metacarpal	Abduction, opposition

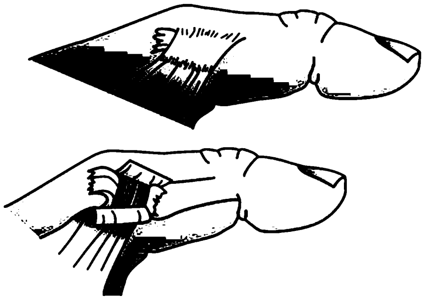


FIGURE 13.63 Gamekeeper's thumb (Seidenberg and Beutler, 2008).

*also indicates complete tear of the UCL (*Fig. 13.64*). Patients usually have significant difficulties with object manipulation, including pinching and grasping activities. Immobilization is usually satisfactory for partial tears. In patients with complete UCL tears, surgical treatment is recommended for acute and chronic injuries, since various surgical techniques has been shown to produce good results for acute injuries* (Campbell, 1955; Mann 1999; Ritting et al., 2010).

Stener lesion

Normally, the UCL lies deep to the AddP tendon. Following the UCL tear, the torn end of the UCL may displace superficial to the adductor aponeurosis/AddP muscle (Fig. 13.64). *This entity is called the Stener lesion. The interposition of the AddP muscle between the UCL and the MCP joint hinders the healing. A stener lesion requires surgical reattachment of the ligament* (Kundu et al., 2012; Lark et al., 2017).

The strength of the ligaments in carpometacarpal osteoarthritis

*The strength of the ligaments of the first CMC joint in various stages of CMC OA was examined. According to the Eaton classification, in stage 1, the AOL lost 51% of its strength, while in stages 2 and 3, the IML had lost 53% of its strength. It was concluded that there was a continuous decrease in all phases of OA in the POL strength (*Najima et al., 1997*). These results may suggest that exercise program that improves the stability of the joint may be beneficial before any radiological changes in the joint occur.*

The progression of the carpometacarpal osteoarthritis

*Synovitis in the TMC joint may cause weakening or partial rupture of the AOL, UCL, and IML ligaments located on the ulnar side of the joint. The ligaments responsible for the stabilization of the joint become unable to resist the forces caused by the pinch. The metacarpal slides toward the dorsal or dorso-radial with respect to trapezium. The shear forces with the potential for damaging are concentrated in the adjacent area of the AOL ligament in the palmar face of the trapezium. The AdP muscle contracture may develop in the late stages of the CMC OA, which may cause narrowing of the web space and causing CMC joint to be dislocated or subluxated (*Fig. 13.65*). When the thumb is adducted, hyperextension develops in the MCP joint due to the spasm or contracture of the AdP muscle and the volar plate at the MCP joint is stretched with excessive stress (*Fig. 13.65*). The bowstringing tendency of the EPB and EPL tendons may contribute to the hyperextension deformity of the MCP joint by increasing the extensor lever force. The IF joint goes to flexion due to passive stretching of the FPL (*Fig. 13.65*). The development of MCF joint hyperextension deformity as a functional compensatory mechanism concentrates the loads in the palmar compartment of the CMC joint and progresses the disease*

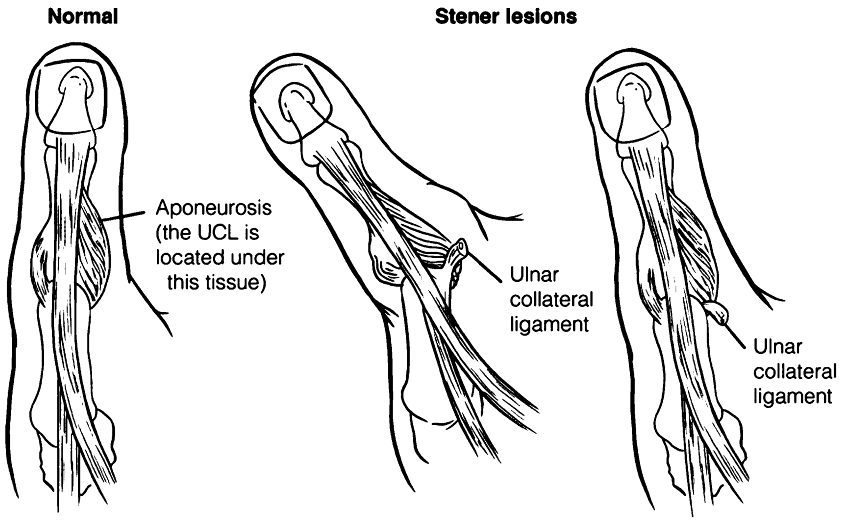

Normal
Stener lesions
Aponeurosis (the UCL is located under this tissue)
Ulnar collateral ligament
Ulnar collateral ligament

FIGURE 13.64 Stener lesions (Sen et al., 2019). *UCL*, Ulnar collateral ligament. *Illustration by Nila Murali.*

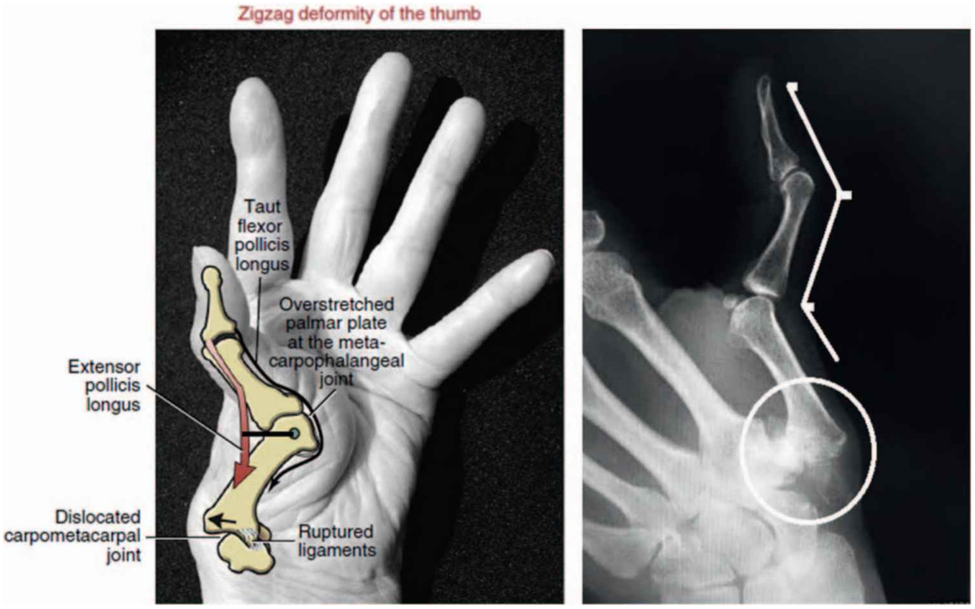

Zigzag deformity of the thumb
Taut flexor pollicis longus
Overstretched palmar plate at the meta-carpophalangeal joint
Extensor pollicis longus
Dislocated carpometacarpal joint
Ruptured ligaments

FIGURE 13.65 The progression of the CMC osteoarthritis: the Z deformity of the thumb (Neumann, 2002). *CMC*, Carpometacarpal.

process. Therefore patients with extension laxity in the MCP without osteoarthritis may be prone to progressive CMC OA.

Innervation patterns of the ligaments

The innervation patterns of the ligaments may give information about the role of ligaments in neuromuscular stabilization of the CMC joint. Hagert et al. investigated the sensory nerve endings of five ligaments (DRL, DKL, POL, AOL, and UCL) that play a major role in stabilization of the joint by immunohistochemical methods. They reported that the ligaments on the dorsal side had significantly more mechanoreceptors and nerve endings than the palmar side of the CMC joint. The density of the innervation of AOL was very low. The Ruffini body is the dominant mechanoreceptor with a greater density in the metacarpal part of each ligament (Hagert et al., 2012). The results suggest that the dorsal ligament complex plays a role in the proprioceptive function of the joint as well as providing static joint stability. The high density of the sensory nerve endings in the dorsal ligaments may explain the pain on the dorsal side, which is often encountered in patients with CMC OA.

Muscles

Thenar muscles

There are nine muscles responsible for the dynamic stabilization of the TMC joint.

Volar muscles include

APB,
OP,
FPB,
flexor pollicis longus (FPL), and
AddP.

Dorsal muscles include

first dorsal interosseous,
extansor pollicis longus,
extansor pollicis brevis, and
APL.

Abductor pollicis brevis

It is located on the outermost part of the thenar region (Fig. 13.66). The APB is a flat, thin, and triangular muscle. It originates from the transverse carpal ligament (flexor retinaculum), the tubercle of the trapezium, and the scaphoid. Some fibers begin from the APL and PL tendons and terminate on the extensor aponeurosis of the thumb. These fibers form the lumbrical muscle of the thumb. APB may also receive accessory fibers starting from EPL, OP, and radial styloid. The medial fibers of APB adhere to the lateral side of the proximal phalanx of the thumb and the lateral fibers to the dorsal aponeurosis of the thumb. The APB muscle abducts the thumb. It also assists thumb flexion and opposition—reposition. The APB is the synergist acting muscles with APL and PL. The APB is innervated by the terminal motor branch of the median nerve (Doyle and Botte, 2003; Duncan et al., 2013).

Flexor pollicis brevis

The FPB muscle is located at the medial side of the APB muscle (Fig. 13.66). The FPB has deep and superficial heads. The superficial head attaches to the retinaculum and the tubercle of the trapezium. It travels along the lateral edge of the FPL tendon and adheres to the radial side of the proximal phalanx and the capsule of MCP joint. The deep head attaches to the trapezium, trapezoid, and capitate bones. It runs distally under the FPL tendon and joins with the superficial head at the lateral side of the FPL tendon. It inserts on the proximal phalanx and the lateral sesamoid bone. Two heads of FBP form a muscular groove in which the FPL tendon extends. The FPB muscle flexes the MCP joint and pronates the first metacarpal. It also assists in opposition, reposition, and adduction movements. The superficial head of this muscle is innervated by the median nerve and the deep head is innervated by the ulnar nerve (Doyle and Botte, 2003; Duncan et al., 2013).

Opponens pollicis

The OP muscle is a triangular, flat muscle that extends deep within the APB muscle (Fig. 13.66). It originates

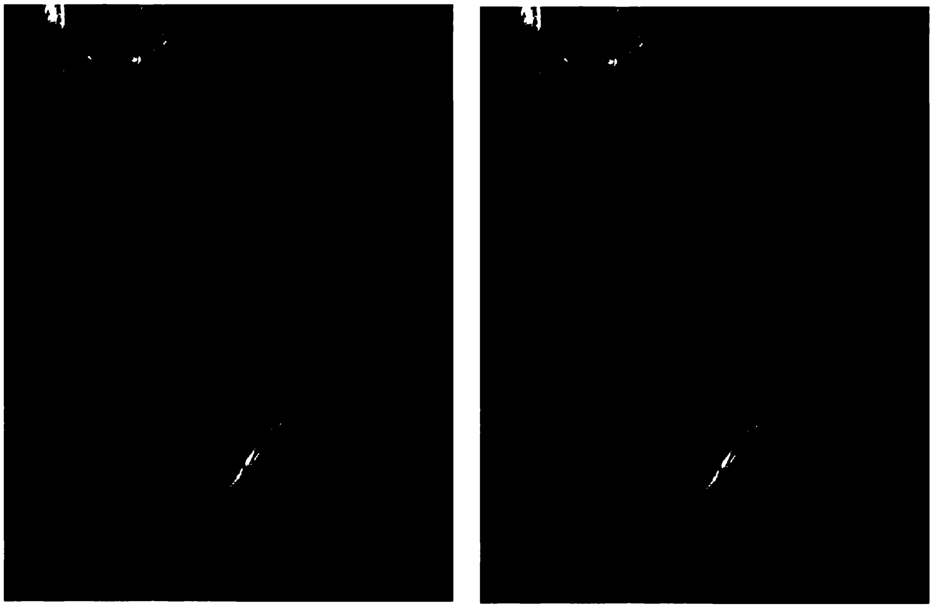


FIGURE 13.66 Thenar muscles. *ADD*, Adductor pollicis; *APB*, abductor pollicis brevis; *FPB*, flexor pollicis brevis; *OPP*, opponens pollicis; *TCL*, transvers carpal ligament (Leversedge, 2008).

from the tubercle of the trapezium and the lateral edge of the flexor retinaculum. It inserts to the lateral edge of the metacarpal. The function of the OP muscle is to oppose the thumb to the fingers. It is innervated by the terminal motor branches of the median nerve (Doyle and Botte, 2003; Duncan et al., 2013).

Median nerve injury

*In median nerve injury, there is a thenar atrophy characterized by flattening of muscle mass (*Fig. 13.67*). The ability of thumb abduction and opposition is lost. The action of the thumb extensor, adductor, and supinator positioned the thumb out of the palm. In low median nerve injury, extrinsic thumb muscles remain intact, whereas in high median nerve injury, both extrinsic and intrinsic muscles are denervated (*Pederson, 2014*). The opposition movement is unique for human being. Following median nerve injury, loss of opposition is a devastating loss for the selective positioning of the thumb for prehension and fine motor manipulation. Grip force is also decreased. The restoration of opposition is a good surgical option, which may increase the hand function of the patients (*Oberlin et al., 1999; Chadderdon and Gaston, 2016*).*

Adductor pollicis

It is the deepest and most medial of the thenar muscles (Fig. 13.66). It has two heads, oblique and transverse. The oblique head originates from the capitate, and the second and third metacarpal and the FCR tendon. The transverse head originates from the 2/3 distal of the palmar surface of the third metacarpal. These two heads insert on the proximal phalanx of the thumb. AddP muscle adducts the thumb. This muscle is innervated by the terminal branches of the ulnar nerve (Doyle and Botte, 2003; Duncan et al., 2013).

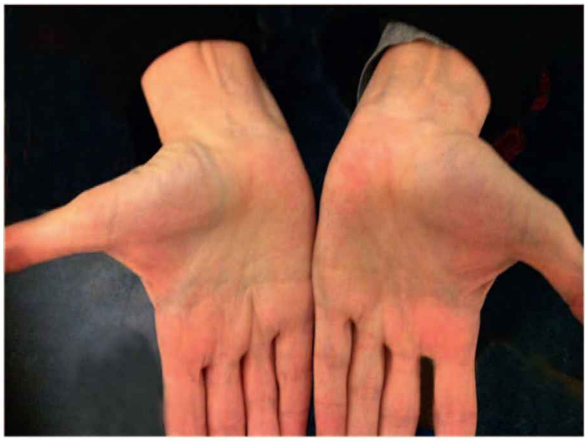


FIGURE 13.67 Atrophy of the right thenar muscles (Leenders et al., 2013).

Froment sign

*Positive Froment's sign is an indicator of the ulnar nerve palsy (*Froment, 1972*). Following ulnar nerve injury, there will be a loss of function of the ulnar nerve innervated AddP muscle. When the patient performs a pinch, thumb IP joint flexes with the activity of the FPL to compensate the weakness of the AddP muscle (*Fig. 13.68*). For the test the patient holds a piece of paper between the thumb and the index finger. The thumb position is observed during the test. The clinician can pull the piece of paper to increase the resistance. However, some conditions may also mimic a positive test result such as shortened thumb metacarpal (*Drury and Stern, 1982*).*

Abductor pollicis longus

The APL muscle attaches to the posterior margin of the ulna, the interosseal membrane, and the dorsal surface of the radius. It continues through the forearm and cross the ECRL and ECRB tendons and pass under the extensor retinaculum. The APL muscle inserts on the first metacarpal and trapezium. The muscle abducts the thumb. It is innervated by the PIN (Doyle and Botte, 2003).

Extensor pollicis brevis

It originates from the one-third distal radius and the interosseal membrane and inserts to the proximal phalanx. The muscle extends the thumb and helps radial deviation of

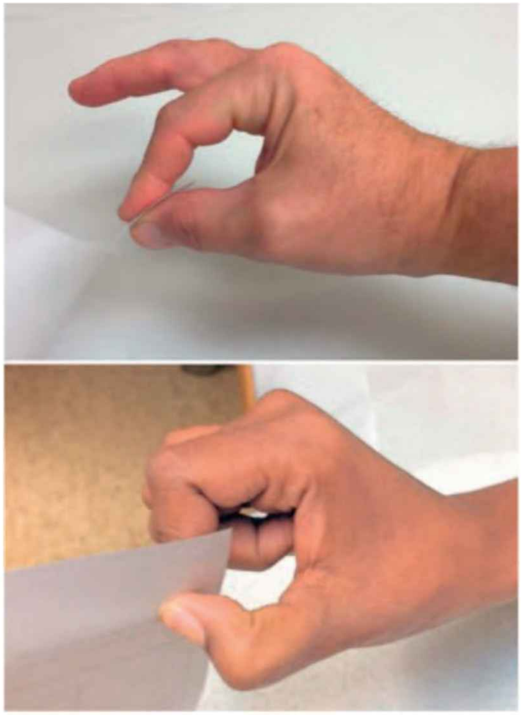


FIGURE 13.68 Froment's sign (Preston and Shapiro, 2012).

the hand. Since this muscle crosses the radio–ulnar axis of the TMC joint externally, it also abducts the thumb. It is innervated by the PIN (Doyle and Botte, 2003).

Extensor pollicis longus

It originates from the interosseal membrane and one-third of the posterior surface of the ulna. It inserts on the base of the distal phalanx of the thumb. The muscle extends the IP joint of the thumb. It is innervated by the PIN (Doyle and Botte, 2003).

First dorsal interosseous

This muscle, also called "abductor indicis," is the largest of the dorsal interosseous muscles. A fibrous arch, in which the radial artery passes, divided the muscle into two heads. The medial head originate from the ulnar surface of the first metacarpal and the lateral head originates from the radial aspect of the second metacarpal. The muscle inserts on the radial side of the basis of the proximal phalanx. It abducts the index finger. It also helps MCP flexion and IP extension via extensor apparatus. The muscle is innervated by the terminal branches of the ulnar nerve (Doyle and Botte, 2003).

Dynamic stabilization of the first carpometacarpal joint

*Selective strengthening of the thumb muscle could help to prevent radial subluxation of the thumb CMC joint. The FDI muscle is the most active thumb muscle during dynamic closed kinetic chain pinch activities. An EMG study on the activation of the FDI muscle in patients with and without OA showed that FDI muscle was weaker in individuals with OA and that the muscle needed longer time to complete certain functional activity (*Calder et al., 2011*). Studies showed that the contraction of the FDI and OP muscles might prevent subluxation of the joint by increasing the contact area at the CMC joint (*McGee et al., 2015; Adams et al., 2018*). The first interosseal muscle (FDI) and OP muscles create an effective force–couple acting on the first metacarpal base.* McGee et al. (2015) *reported that FDI muscle activation reduced the radial subluxation of the CMC joint by directing the first metacarpal onto the trapezium. Conversely, the isometric contraction of the EPL and APL muscles concluded to increase the compression and shear forces at the CMC joint (*Mobargha et al., 2016*). Therefore the activation of these muscles should be avoided when planning exercise program.*

Bennett fracture

*The Bennett fracture involves the first metacarpal base of the thumb, which occurs due to axial loading on a partially flexed metacarpal. This fracture is an intraarticular fracture that separates the palmar ulnar fragment from the metacarpal shaft (*Fig. 13.69*). The ulnar palmar fragment maintains its position by its ligamentous attachment to the trapezium via anterior oblique ligament. The first metacarpal shaft subluxes dorsally and radially due to the pull of the APL, EPL, EPB, and AddP. The reduction requires an axial traction with abduction and pronation while applying pressure over the base of the first metacarpal (*Edmunds, 2006; Carter and Nallamothu, 2018*).*

Metacarpophalangeal joints of the fingers

The MCP joints are located between the convex heads of the metacarpals proximally and the concave base of the first proximal phalanges distally (Fig. 13.70). The structure and function of the MCP joints are similar throughout the five fingers. However, the MCP joint of the thumb and those of the fingers exhibit small differences in structure.

The MCP joints of the fingers are described as condyloid or biaxial type synovial joints with two degrees of freedom: flexion/extension and abduction/adduction. The joint surfaces are convex on the metacarpal side and concave on the phalangeal side. The metacarpal head has 180 degrees of articular surface in the sagittal plane. The joint surfaces of the metacarpals have asymmetrical small tubercles except the middle finger (Pagowski and Piekarski, 1977; Brand, 1993; Clavero et al., 2003; Hirt et al., 2017; Hirth et al., 2017).

The supporting structures of the MCP joints include the capsule, collateral ligaments, and the volar (palmar) plates (Fig. 13.71). In addition, the joints are supported by the transverse IML, the accessory collateral ligaments and the surrounding tendons, and associated soft tissue. The MCP joint is surrounded by a capsule, which is lax in extension. This capsular laxity and incongruent articular surfaces allow some axial rotation of the proximal phalanx.

The capsule was supported by this strong fibrocartilage structure called palmar volar plate. Synovial sheaths of the flexor tendons also participate in this structure. Volar plate can separate bony fragment from the base of the proximal phalanges and the metacarpal head while dislocation occurs. The dorsal of the joint is composed of loose structures. Dorsal capsule is thin and weak. It contributes minimally to joint stability. The MCP joints are linked by the strong deep transverse ligaments (deep trasverse palmar ligament) that span the heads of the second through fourth metacarpals volarly. It is blended with the palmar MCP ligaments. This ligament prevents the attached metacarpals from abduction at the CMC joints.

The volar plate (palmar plate) provides a protective fibro-cartilaginous covering for the articular surfaces,

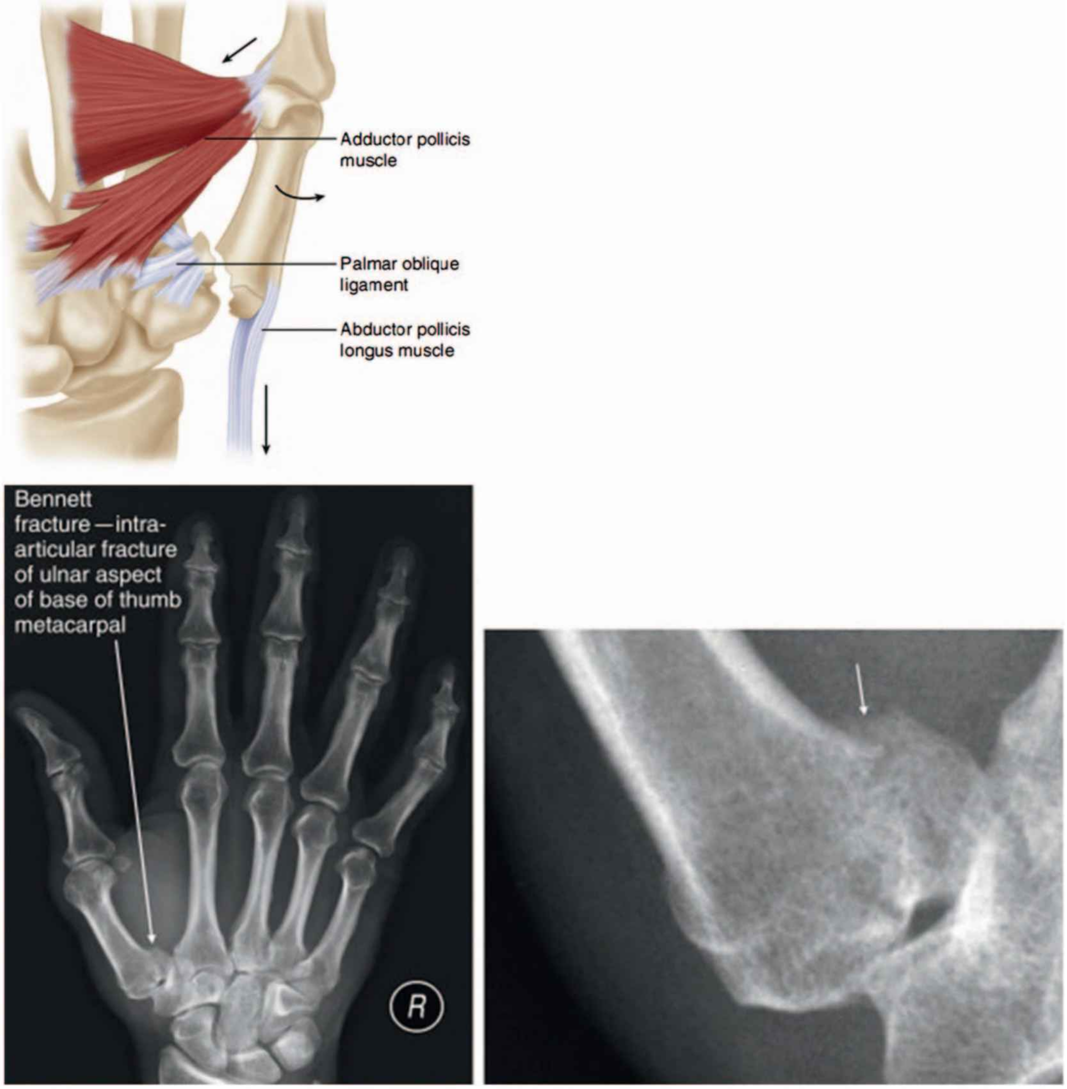

Adductor pollicis muscle
Palmar oblique ligament
Abductor pollicis longus muscle
Bennett fracture—intra-articular fracture of ulnar aspect of base of thumb metacarpal
R

FIGURE 13.69 Bennett's fracture. Subluxation of the first metacarpal shaft dorsally and radially due to the pull of the APL, EPL, EPB, and adductor pollicis (Preston and Shapiro, 2012). *APL*, Abductor pollicis longus; *EPB*, extensor pollicis brevis; *EPL*, extensor pollicis longus.

which increases joint congruence. It increases anteroposterior stability of the MCP joint by limiting hyperextension. This serves an important protective role by during grasping by indirectly supporting the longitudinal arch. The volar plates protect the surface of the metacarpal heads from abrasion by the object in the hand (Fig. 13.72). Activities involving powerful grasp of a large object could increase the risk of damage to the metacarpal heads without the protection of the volar plates. The volar plates firmly attached to the base of the proximal phalanx distally but loosely attached to the metacarpal proximally. They blend with the deep transverse metacarpal ligament, which tethers together the heads of the metacarpal heads. Sagittal bands that lie dorsal to the deep transverse ligament connect each volar plate via the capsule and deep transverse metacarpal ligament to the extensor hood. Fibrous sheaths attach superficially to the anterior side of the volar plates.

Axial stability is provided by collateral ligaments, accessory collateral ligaments, and interosseous–lumbrical muscles. The radial and UCLs provide lateral stability of the MCP joints (Fig. 13.73). The collateral ligaments originate from the posterior tubercule on the lateral sides of the metacarpal head. They run obliquely to the proximal phalanx and insert on the palmar site of the lateral surface of the base of the proximal phalanx. The radial and UCLs have broad attachments on the sides of the metacarpal heads and proximal phalanges. The RCLs are thicker and wider than the ulnar ligaments. These ligaments are composed of two parts: the collateral ligament proper and the accessory collateral ligament. The collateral ligament proper is located

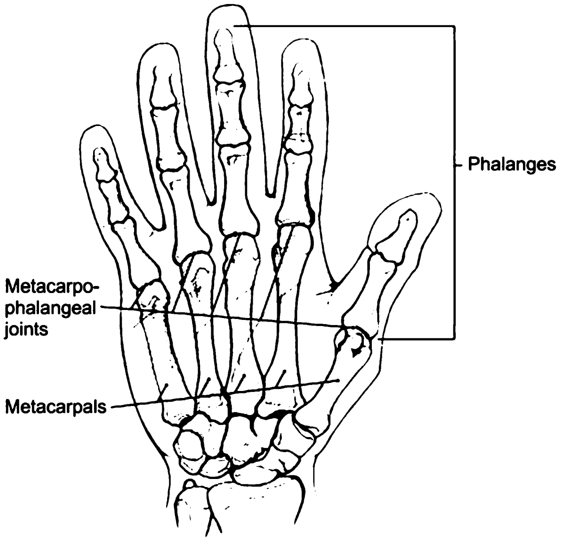


FIGURE 13.70 Anatomy of the metacarpophalangeal joint (Waldman, 2009).

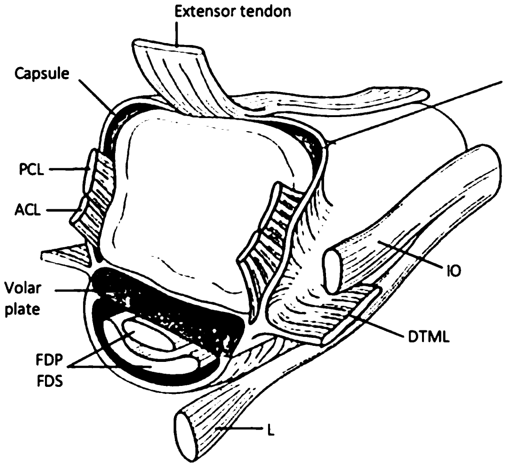


FIGURE 13.71 The supporting structures of the MCP joints (Prosser and Conolly, 2003). *MCP*, Metacarpophalangeal.

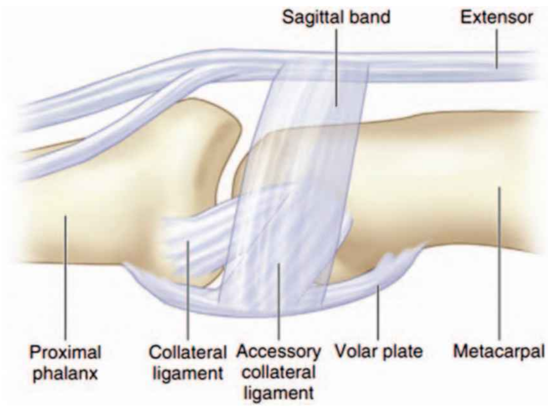


FIGURE 13.72 Volar plate (lateral view) (Chung, 2019).

dorsally to the flexion–extension axis of the joint. It progressively tightens with MCP joint flexion (Fig. 13.73). The accessory collateral ligament lies palmarly to the flexion–extension axis of the joint. The ligament is stretched at extension and resists the dorsal dislocations with the volar plate. Since the collateral ligaments on either side of the MCP joints become taut when the joint goes from extension to flexion, they prevent abduction and adduction of the MCP joints. This is also because each metacarpal head has not a complete spherical structure. Although it is rounded at its distal part, it is flattened anteriorly and takes trapezoidal shape in the axial section. When the base of the proximal phalanx moves onto this flattened surface, the volar surface of the metacarpal head resulted in a bony block at 70 degrees of MCP joint flexion causing limitation of the abduction–adduction (Werner et al., 2003; Lutsky et al., 2014).

Osteoarthritis

There is a small incidence of osteoarthritis (OA) in MCP joints in comparison with common changes seen in the DIP joints and, to a lesser extent, in the PIP joints. Fisher et al. found that there is a fibrocartilage structure located at MCP, PIP, and DIP joints, which spans from the volar plates, from the collateral ligaments and the extensor hood. The projections of this fibrocartilage are broader at the MCP joints, increasing the contact area of the base of phlanges with the metacarpal head.

Kinematics

The MCP joint allows flexion and extension within the sagittal plane and allows abduction and adduction with in the frontal plane. The MCP joint flexes approximately 90 degrees and may extend about 20–30 degrees. The abduction–adduction arc depends on the specific digit and it is about 10–40 degrees. Some rotation and deviation also occur during flexion,

The shapes of the metacarpal bones differ among the four fingers. Some studies report that the axis of flexion and extension remains fixed in the center of the metacarpal head. Others suggest that the axis moves in a volar direction during flexion and in a dorsal direction during extension. The flexion excursion of the ulnar fingers is greater than the radial fingers allowing the finger tips to come into line with one another when the hand is closed (Fig. 13.74). The reference for abduction and adduction movement at the MCP joints is an imaginary line drawn through the middle finger when it is in anatomic position. Movement toward this line is adduction and movement away from this line is abduction. Since the frontal plane movement of the middle finger in either direction (starting from anatomic position) is away from this line, both

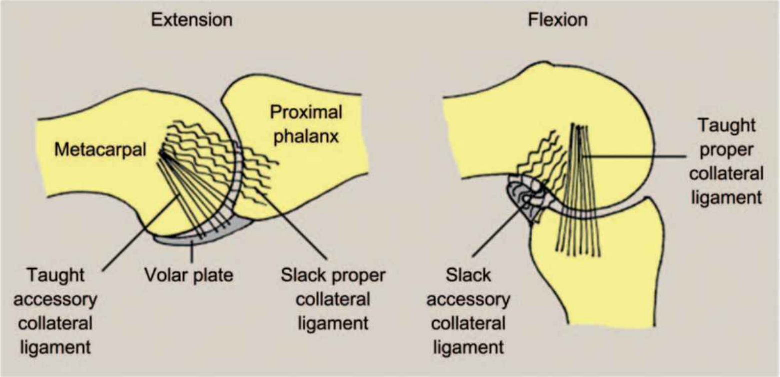

Extension
Flexion
Metacarpal
Proximal phalanx
Taught accessory collateral ligament
Volar plate
Slack proper collateral ligament
Slack accessory collateral ligament
Taught proper collateral ligament

FIGURE 13.73 Collateral ligaments of the MCP joint (Newton et al., 2019). *MCP*, Metacarpophalangeal.

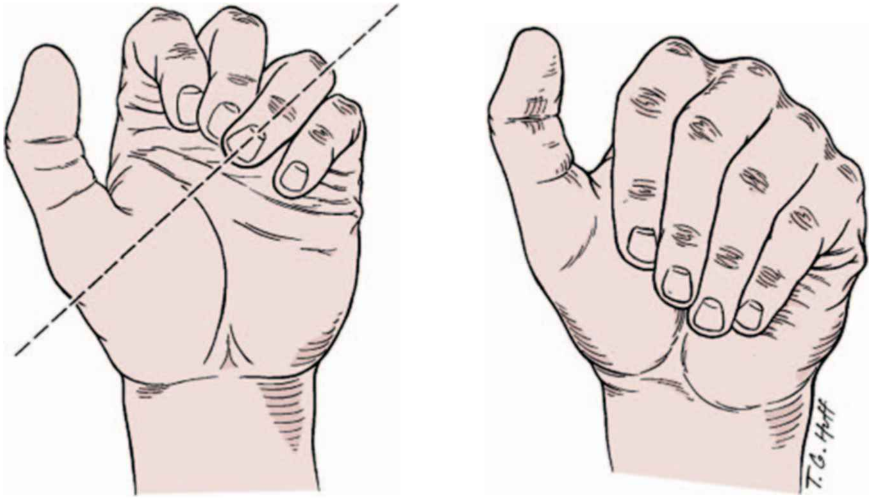


FIGURE 13.74 Fingertips normally point toward the scaphoid. Deviation of the fingertips may indicate a rotational deformity following a metacarpal fracture (Giangarra and Manske, 2017).

directions of movement are termed abduction. Lateral movement of the middle finger is termed radial abduction and medial movement of the middle finger is termed ulnar abduction (Oatis, 2009; Hirt et al., 2017; Hirth et al., 2017).

Interphalangeal joints of the fingers

IP joints are located between phalanges of the fingers. The IP joint located between the proximal and middle phalanges is called the PIP joint. The IP joint located between the middle and distal phalanges is called the DIP joint. There are nine IP joints in the fingers, four proximal IP (PIP), and four distal IP (DIP) joints in the fingers and a single IP joint in the thumb. Each IP joints are synovial hinge joints (Pang and Yao, 2018). The head of a phalanx articulates with the base of the phalanx distal to it. The joint surfaces are covered by articular cartilage. The proximal articular surface is larger than the distal articular surface (Shrewsbury and Johnson, 1980; Allison, 2005).

The supporting structures of these joints are similar, including a capsule, collateral ligaments, and a volar plate (Fig. 13.75). The capsules surround the joint surfaces. The collateral ligaments include proper and accessory parts similar to MCP joints. These collateral ligaments provide lateral stability to the joints throughout the range of flexion and extension excursion. The collateral ligaments do not allow abduction–adduction in the joint (Bailie et al., 1996; Stollwerck et al., 2010).

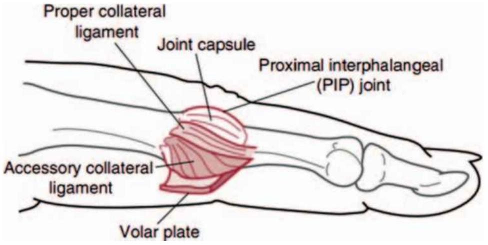

Proper collateral ligament
Joint capsule
Proximal interphalangeal (PIP) joint
Accessory collateral ligament
Volar plate

FIGURE 13.75 The supporting structures of the PIP joint (lateral view) (Giangarra and Manske, 2017). *PIP*, Proximal interphalangeal.

Volar plates enhance stability of each joint in the anteroposterior direction by limiting hyperextension and protecting the volar surface of the head of each phalanx. The structure and function of the volar plates are similar to

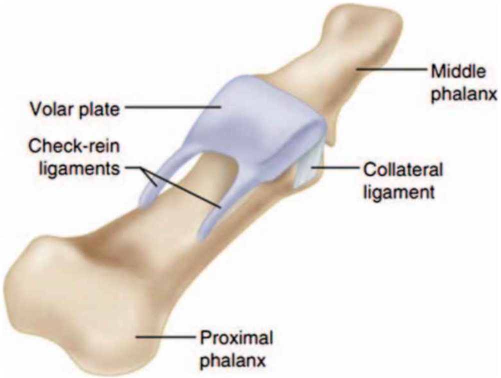


FIGURE 13.76 The volar plate of the PIP joint. Proximal check-rein ligaments are shown (Chung, 2019). *PIP*, Proximal interphalangeal.

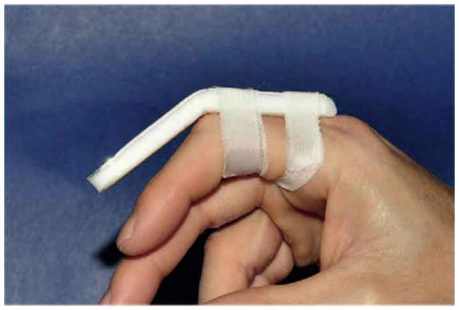


FIGURE 13.77 Extension block splinting techniques allow full active flexion and prevent extension beyond the stable range (Williams, 2012).

those at the MCP joints, but the volar plates are not connected by a deep transverse ligament.

The volar plates of the PIP joints are thicker than that of the DIP joints (Fig. 13.76). Palmar checkrein ligaments enhance the stability of the volar plates attached strongly to the middle phalanx (Fig. 13.76). The structure of the DIF joints is similar to PIF joints. But there is no checkrein ligament in DIF joints. DIF joint stability is less than PIF (Stollwerck et al., 2010; Pang and Yao, 2018). Pulp contact increases DIF stability. Hyperextension of the DIP is greater than that of the PIP joints due to the structure of the volar plates underlying each joint surface. The surrounding flexor and extensor tendons also provide a substantial dynamic stability to the IP joints (Shrewsbury and Johnson, 1980; Dyson et al., 2008).

Volar plate injury

Volar plate injuries usually occur with forced hyperextension in younger individuals particularly those involved in sports. The proximal checkrein ligaments are stronger than the distal attachments to the middle phalanx. Therefore volar plate rupture frequently occurs distally. Pain with passive hyperextension of the finger, tenderness over the volar region of the joint are the most common indicators of the volar plate injury. Conservative treatment is appropriate in the injuries that involve less than 30%–40% PIP joint surface and are reducible in less than 30 degrees flexion. The PIP extension-blocking splint (PIP joint is positioned in 20–30 degrees flexion) is recommended in these patients (Fig. 13.77), (Bowers, 1981; Pattni et al., 2016*).*

Collateral ligament injury

*Collateral ligament injury is a common injury encountered by clinicians. The lateral collateral ligament is an important stabilizer of the lateral deviation of the finger and the UCL maintains ulnar stability. However, the volar plate provides anteroposterior stability; it also contributes to lateral stability when the collateral ligaments are incompetent (*Kiefhaber et al., 1986*). Incomplete rupture of the collateral ligaments is usually treated with immobilization. If the lateral stress test shows more than 20 degrees of varus or valgus deformity in extension, this sign will indicate complete collateral ligament injuries (*Kiefhaber et al., 1986*). Surgical repair is recommended for the complete injuries. Operative treatment provides good results regarding the joint stability, pain and cosmetic appearance (*Lee et al., 2017*).*

IP joints have one degree of freedom allowing two major motions—flexion and extension. However, slight radioulnar deviation and rotation also occur at these joints during flexion and grasping. These accessory movements are important since they help directing the fingers toward the thumb. The total range of flexion at the PIP joint is 110 and 80 degrees at the DIP joint. However, there is a different flexion pattern of the fingers due to the bony structure of the phalanges. The PIP and DIP joints at the ulnar fingers have greater flexion ranges (135 and 90 degrees) than those of the radial digits. The condyles of the proximal phalanges are slightly asymmetrical. This anatomical variation makes the flexion–extension axis of motion slightly tilted with respect to the long axis of the fingers. During the flexion–extension movements of the fourth and fifth fingers, some axial rotation movement also occurs. Axial rotation movement helps the convergence of the fingers and thumb toward the thenar eminence during finger flexion. The articular surfaces of the DIP joints are more symmetrical, and motion at these joints occurs in planes parallel to the long axes of the fingers. The IP joint of the thumb exhibits less flexion range than the IP joints of the fingers. The PIP joints of the fingers exhibit more flexion than the MCP or DIP joints of the fingers. While minimal hyperextension is present at the PIF joint, approximately 30 degrees hyperextension occurs at the DIF joint.

Functional position of the hand

*The wrist is positioned approximately 20 degrees of extension and 10 degrees of ulnar deviation. The MCP joints are flexed to 45 degrees and the IP joints are slightly flexed. Thumb positioned in slight opposition with slight MCP and IP flexion (*Boscheinen-Morrin and Conolly, 2001; Saunders et al., 2016*).*

Antideformity position of the hand

*Following a hand trauma, a custom-fabricated static splint is used to immobilize the injured structures during the healing process while minimizing potential stiffness and contractures at the joints caused by immobilization. Since the collateral ligaments are slack in extension, immobilization in extension would lead to adaptive shortening of the ligaments resulting in MCP flexion limitation. An antideformity immobilization splint therefore should position the MCP joints in approximately 75 degrees flexion to prevent collateral ligament tightening, IP joints in extension to prevent IP joints flexion contractures, and thumb in abduction and extension to prevent a first web space contracture. This immobilization position is also defined as "intrinsic plus position" in the literature (*Boscheinen-Morrin and Conolly, 2001; Saunders et al., 2016*).*

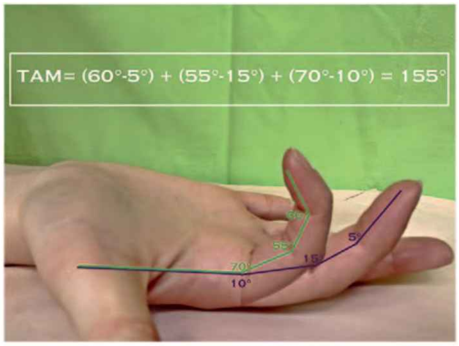


FIGURE 13.78 Measurement of the total active motion.

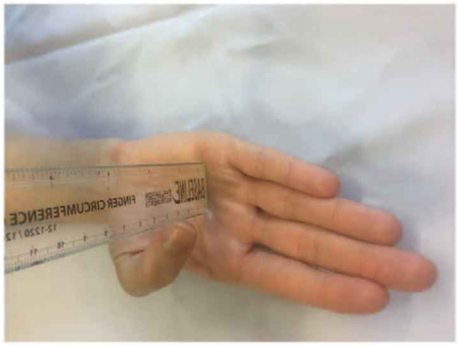


FIGURE 13.79 The measurement of the composite finger flexion.

Range of motion assessments

ROM can be assessed with different techniques, including active ROM (AROM), active assistive ROM (AAROM), passive ROM (PROM), total active motion (TAM), and total passive motion (TPM). AROM is movement produced by individual's own muscle (Giladi and Chung, 2013; Kenney and Hammert, 2014). AAROM is movement produced by individual's own muscle and an external force such as examiner's muscle force. AROM and AAROM measurements depend on the patient's compliance and the experience of the examiner. PROM is movement produced by an external force. Although PROM appears to be a more objective measurement, it is more difficult to control and quantify the applied force (Pratt and Ball, 2016). Any difference between AROM and PROM is referred to as a "lag" and usually indicates loss of tendon glide or function. Difference between AROM and PROM and fixed deformities should be recorded. TAM, TPM, and composite flexion measurements are used to determine the total mobility of a finger that also indicates the tendon excursion (Skirven, 2011; Clarkson, 2013). TAM and TPM measurements are described by the American Society for Surgery of the Hand. TAM is calculated by subtracting extension deficits from active flexion measurements of MCP, PIP, and DIP joints of an individual digit (Fig. 13.78). This calculation is then compared to the TAM of the contralateral hand or the norm of 260 degrees. TPM is calculated by subtracting extension deficits from passive flexion measurements of MCP, PIP, and DIP joints of an individual digit (Bindra et al., 2003; Giladi and Chung, 2013).

The normal tenodesis effect of the wrist should be evaluated following the measurements. Since the extrinsic finger flexors and extensors cross several joints, movement in one joint is affected by the movement of the other (Gerhardt et al., 2002). During the finger measurements the forearm should be kept in pronation, the wrist in neutral position, and the ulnar and radial deviation of the wrist should be prevented (Giladi and Chung, 2013). Shoulder, elbow, and wrist ROM should be also measured and compared with the contralateral side.

The composite finger flexion can also be measured as the distance between the fingertip of each finger and the distal palmar crease with a ruler in centimeters (Fig. 13.79).

Torque ROM is the movement of the joint against a constant external load (200, 400, 600, and 800 g). It is a more reliable method among the passive motion measurements (Fig. 13.80), (Breger-Lee et al., 1993).

Steps to follow during the ROM measurements:

Composite finger flexion and extension should be measured in neutral/mild extension of wrist. To

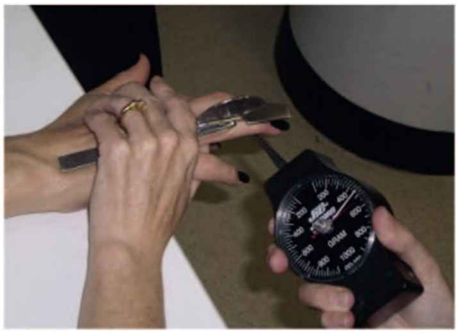


FIGURE 13.80 The measurement of the torque ROM (Glasgow et al., 2011). *ROM*, Range of motion.

evaluate extrinsic tendon tension or adhesions, composite finger flexion and extension can be also measured at full flexion and extension of the wrist.

MCP, PIP, and DIP joint movements should be measured separately for each finger. The proximal joints are positioned in neutral position during measurements to demonstrate whether the limited motion is due to joint stiffness of the associated joint regardless of proximal joints.

AROM and PROM should be both measured for each finger. Comparison of PROM and AROM provides information about tendon adhesions that limit can active movement.

Documentation of range of motion measurements

According to American Medical Society, flexion measurement is recorded as (+) and extension measurement is recorded as (−) with a starting position of 0 degrees

PIP PNEH: 30/110 (30 degrees flexion contracture, full passive flexion)

PIP PNEH: −30/110 (30 degrees hyperextension, full passive flexion)

According to American Society of Hand Therapist extension deficit is recorded as (−) and hyperextension is recorded as (+) with a starting position of 0 degrees

PIP PNEH: −30/110 (30 degrees extension deficit, full passive flexion)

Normative range of motion values

Normative ROM values of the wrist and hand are as follows:

Wrist:

90 degrees flexion, 70 degrees extension, 20 degrees radial deviation, 35−45 degrees ulnar deviation

Finger:

MCP: 90 degree flexion, 25 degree extension, 45 degree abduction
PIP: 120 degree flexion
DIP: 75 degree flexion

Thumb:

CMC: 45 degree flexion, 80 degree abduction
MCP: 45−60 degree flexion
IP: 80 degree flexion

Flexor system

The flexor system of the hand consists of the flexor muscles of the forearm, their tendinous extensions, and the digital flexor sheaths. These components work in concert to produce smooth and efficient flexion of the individual digits of the hand. The digital flexor muscles include the flexor digitorum profundus (FDP), flexor digitorum superficialis (FDS), and the FPL (Fig. 13.81), (Oatis, 2009).

The FDP and FDS tendons of the fingers cross five regions: the wrist, the carpal tunnel, the part of the palm extending from the exit of the carpal tunnel to the entrance of the fibrous flexor sheath, the portion of the osteofibrous canal of the fingers (digital canal) from the MP joint to the half of the middle phalanx, and the distal segment of the digital canal, which transmits only the FDP tendon (Skirven, 2011).

The tendon of the FPL also crosses five regions: the wrist, the carpal tunnel, the thenar eminence, the digital canal, which extends from the opening of the proximal pulley at the volar plate of the MP joint down to the exit of the “oblique pulley” halfway down the proximal phalanx, and the distal segment, which reaches the insertion of the tendon on the base of the distal phalanx (Doyle and Botte, 2003).

The FDP muscle is a long, flat, and strong muscle lying in the deep volar muscle compartment of the forearm. Its innervation is from AIN (branch of the median nerve) to the index and long finger; ulnar nerve to the ring and small fingers. It originates from the proximal two-thirds of the median and anterior surface of the ulna, interosseous membrane, and deep fascia of the forearm and inserts to the base of the distal phalanges (Hirt et al., 2017; Hirth et al., 2017).

The FDP muscle has a single large muscle belly. The belly to the index finger is usually separate. The muscle then divides into four parts. The myotendinous junction gives rise to four separate tendons aligned parallel to each other, which are located radial to ulnar and extends distally to the index, long, ring, and small fingers. However, the FDS tendons to the long and ring fingers located palmar and central to the FDS tendons of the index and small fingers, which are located dorsal and radial (index finger) and ulnar (for the small finger). The muscle belly to the long, ring, and small fingers remain interconnected from the forearm to the palm through areolar tissue and tendinous slips. The FDP tendon to the small finger may be more independent like the index finger (Neumann, 2003; Oatis, 2009). The least independent tendons are those to

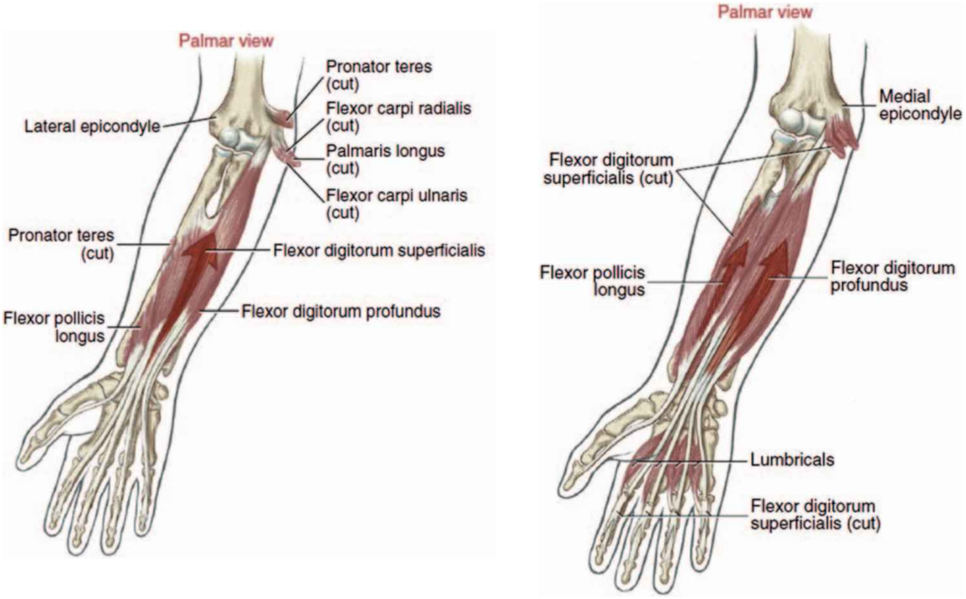

Palmar view
Pronator teres (cut)
Flexor carpi radialis (cut)
Lateral epicondyle
Palmaris longus (cut)
Flexor carpi ulnaris (cut)
Pronator teres (cut)
Flexor digitorum superficialis
Flexor pollicis longus
Flexor digitorum profundus
Palmar view
Medial epicondyle
Flexor digitorum superficialis (cut)
Flexor pollicis longus
Flexor digitorum profundus
Lumbricals
Flexor digitorum superficialis (cut)

FIGURE 13.81 Flexor muscles of the fingers (Neumann, 2010).

the long and ring fingers. The tendons run distally deeply to the tendons of the FDS. At the level of the distal margin of the carpal tunnel, lumbrikal muscles originate from the radial aspect of the FDP tendons. The FDP tendons then enter A1 pulley of the fibro-osseous tunnel. At the level of the proximal phalanx, FDP tendon passes through the split of the FDS and inserts on the base of the distal phalanges (Doyle and Botte, 2003; Oatis, 2009).

The FDP muscle primarily flexes the DIP joints of the fingers but also contributes the flexion of the PIP, MCP, and wrist joints. They functions as the origin for the lumbrical muscles. The contraction of the FDP results in dynamic action on the lumbrikal muscles (Oatis, 2009; Skirven, 2011; Hirt et al., 2017; Hirth et al., 2017).

Quadriga phenomenon

*The FDP muscle has common muscle belly for second–fifth fingers. But also, the tendons of the FDP muscle are interconnected via multiple layers of synovial membranes (*Fig. 13.82*). These cross-connections prevent independent movement of the tendons. This interdependent structure of the FDP muscle is attributed as the effect of quadriga phenomenon. The quadriga phenomenon should be considered in several clinical situations, including strength test of FDP, assessing tendon excursion, and designing an exercise for the FDP muscle* (Schreuders, 2012).

Because of the quadriga effect, holding one or more fingers in extension prevents the excursion of the other FDP tendons. This effect can be assessed clinically. When the index finger is extended, the FDP tendon of the index finger is pulled distally, and the FDP tendon of the middle and the ring finger become lax losing its ability to actively flex their DIP joints (Smith, 1974; Schreuders, 2012). If one holds a pencil with the index finger, the other fingers cannot be extended due to the effect of intertendinous connections between the FDP tendons.

FIGURE 13.82 Flexor profundus tendon to index finger (A). Flexor profundus tendons to long, ring, and small fingers (B). Oblique tendinous slip from index finger to ulnar three profundi (C) (Malerich et al., 1987).

Muscle test of the flexor digitorum profundus and flexor digitorum superficialis muscles

The quadriga effect can be used to isolate the FDP muscle when performing isolated muscle testing of the FDS *muscle. The excursion and the strength of the FDS muscle are tested by holding the adjacent fingers in extension (*Fig. 13.83*). When the adjacent fingers are extended, the FDP tendon is pulled distally of those fingers, which prevents the DIP flexion of the tested finger. The PIP joint flexion is possible for that finger that is flexed by the FDS (*Schreuders, 2012*).*

The strength and excursion of the FDP tendon should be assessed with all fingers in flexion to prevent the inactivation of the FDP muscle. The examiner applies external force by attempting to extend the DIP joint (Fig. 13.84) (Schreuders, 2012).

Flexor digitorum superficialis (flexor digitorum sublimis)

The FDS is one of the superficial muscles of the forearm along with the PT, FCR, PL, and FCU. It is innervated by a branch from the median nerve. The FDS muscle has two heads with separate origins: humeroulnar and radial head. The humeroulnar head arises from the medial epicondyle of the humerus and from the proximal medial ulna. The radial head originates from the volar proximal radial shaft. The two heads form a muscular arch, which is a potential site for median nerve compression.

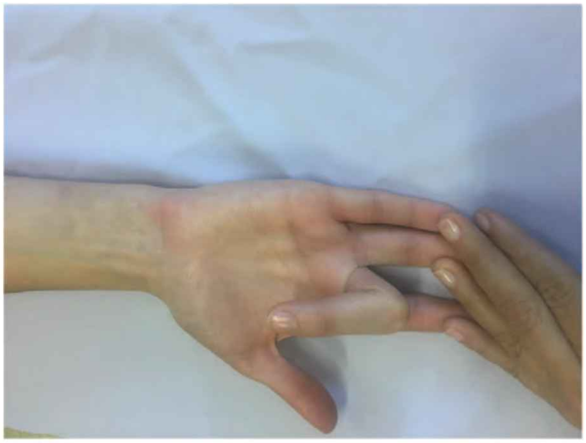


FIGURE 13.83 Isolated muscle testing of the FDS. *FDS*, Flexor digitorum superficialis.

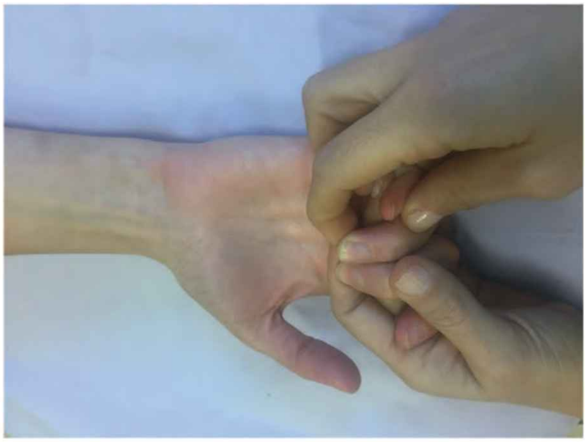


FIGURE 13.84 Muscle testing of the FDP. *FDP*, Flexor digitorum profundus.

The muscle belly of the FDS forms two separate submuscle bellies: deep and superficial plane. The superficial plane further divides into two parts and continues to the long and ring fingers. The deep pair continues to the index and small fingers. At the wrist level the superficial pair is located centrally, whereas the deep pair is located radially and ulnarly. The tendons diverge from one another in the palm and extend distally deep to the superficial palmar arch and the digital branches of the median and ulnar nerves. At the level of the base of the proximal phalanges, each tendon divides into two slips. The divergence of the two slips forms an interval through which the associated tendon of the FDP passes. The two slips of the FDS reunite at Camper's chiasma. Each slip of the tendon of the FDS inserts into the medial and lateral aspects of the volar shaft of the associated digit.

The FDS flexes the PIP joints. It also contributes to flexion of the MCP and wrist joints. The FDS has independent muscle bellies unlike the FDS muscle; therefore it can flex PIP joints independently.

Flexor pollicis longus

The FPL muscle is one of the deep flexors of the forearm. It is innervated by the median nerve through AIN. It originates from the anterior surface of the middle third of the radius. At the level of the MCP joint the tendon enters the fibro-osseous tunnel through the A1 pulley and then inserts to the base of the distal phalanges. The FPL muscle flexes the thumb IP joint. It contributes the flexion of the MCP and CMC joint.

Linburg–Comstock anomaly

*There can be interconnections between the FDP tendon of the index finger and the FPL tendon to the thumb, which is called Linburg–Comstock anomaly (*Linburg and Comstock, 1979*). The interconnection is usually found near the carpal tunnel (*Nakamura and Kubo, 1993*). This interconnection prevents the independent DIP flexion of the index finger without the flexion of the IP joint of the thumb (*Fig. 13.85*). This connection can be tested with the patient extending all fingers while flexing the IP joint of the thumb. If there is a connection between the FPL and the* second *FDP tendons, the index finger will be pulled into flexion (*Schreuders, 2012*).*

Neuropathy of the anterior interosseous nerve

AIN is the terminal motor branch of the median nerve. It arises from the median nerve 4–6 cm distal to the medial *epicondyle (*Fig. 13.86*). AIN innervate 3 muscles, including 2–3 FDP, FPL, and pronator quadratus. It has no cutaneous sensory innervation. The common site of the compression is the tendinous edge of the pronator teres.*

Complete neuropathy of the AIN results in motor deficit of muscles innervated by AIN. Patient with Martin–Gruber anastomoses may result in incomplete neuropathy. Martin–Gruber anastomose is presented when the axons of the AIN connect to ulnar nerve and innervate also intrinsic muscles. AIN neuropathy results in motor deficit only. Patients do not have any complaints of pain due to the absence of the cutaneous sensory innervation of the AIN. The weakness of the FPL and second FDP is tested by asking to patient to make OK sign.

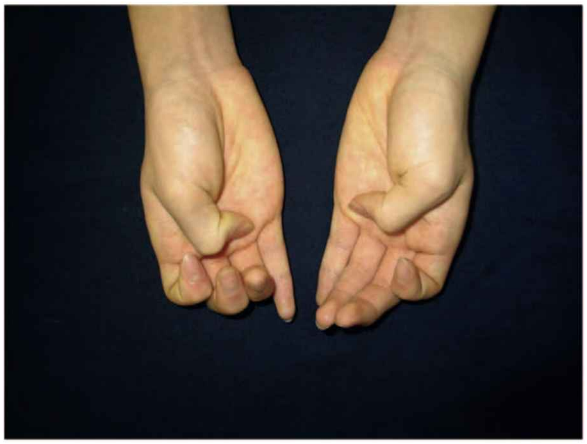


FIGURE 13.85 Flexion of the index, middle, and ring fingers with simultaneous thumb flexion was observed in the right hand. Simultaneous flexion of the index finger was also observed in the left hand (Yoon and Kim, 2013).

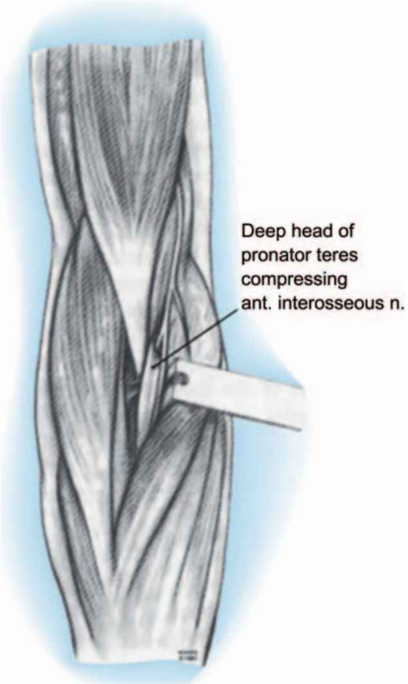

Deep head of pronator teres compressing ant. interosseous n.

FIGURE 13.86 The common site of the compression is the tendinous edge of the pronator teres (Morrey et al., 2017).

Flexor tendon zones

Flexor tendons are divided into five zones according to surgical anatomical features. Flexor tendon injuries are defined according to these zones (Fig. 13.87), (Kleinert and Verdan, 1983; Strickland, 2005; Skirven, 2011; Asmus et al., 2015).

Zone I: This region includes the distal part of the FDP tendon. The flexion loss of the DIP joint is seen due to FDP tendon injury. The tendon excursion is very small in this zone (5–7 mm). Therefore even a minimal reduction in the amount of tendon excursion affects the DIP flexion substantially. Loss of flexion in the interpalangeal joint will decrease the grip force of the fingertip. However, adhesion is less common in isolated FDP injuries.

Zone II: The region locates between the FDS insertion to distal palmar crease. In this zone the FDP and FDS flexor tendons enter the same fibrous sheath. Since the FDS and the FDP tendons can be both injured in Zone II injuries. This zone has poor results than the other zones due to increased risk of adhesions. Generally, neurovascular structures are also associated with injury.

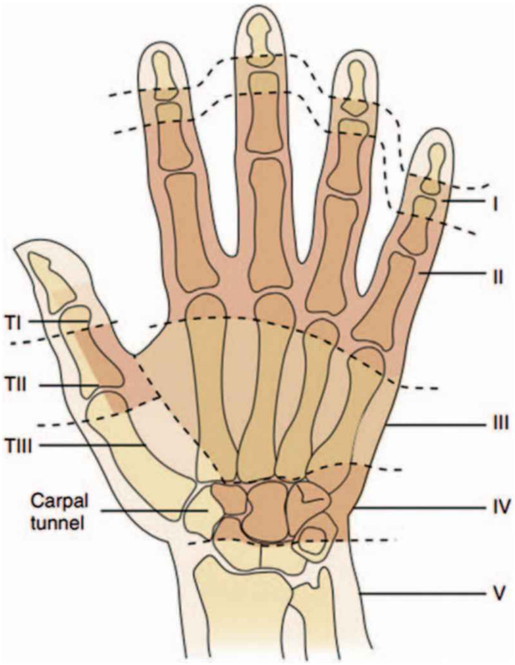


FIGURE 13.87 Flexor tendon zones (Magee et al., 2016).

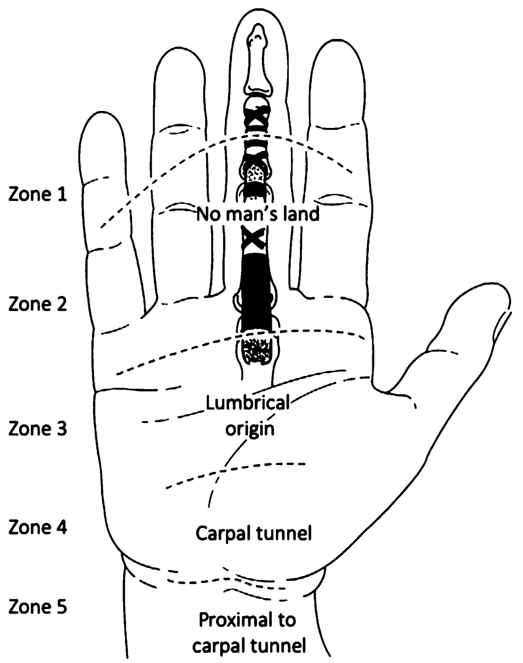


FIGURE 13.88 Illustration of the Zone II "no man's land" (Eastman et al., 2008).

Adhesions and complications are the most common site. Bunnell calls this zone the "No Man's Land" (the area that no one should touch) because of its complex anatomy (Fig. 13.88). It is also named as "the critical zone" in the literature. It is emphasized that nonspecialists should not interfere with lesions in this region because of the high likelihood of adherence of the tendon to the surrounding tissues in the postoperative period. The adhesions are seen between the tendon–tendon sheath, tendon–bone, and other soft tissues, especially between FDP and FDS. The tendon function is adversely affected by the damage of the tendon pulley system. Especially the damage of the tendon sheath both adversely affects the diffusion of the tendons through synovial sheaths and increases adhesion formation.

Zone III: This zone extends from the distal palmar crease (A1 pulley) to the distal margin of the carpal tunnel. Adhesions are usually seen between adjacent tendons, lumbrical muscles, interosseal muscles, and palmar fascia.

Zone IV: This zone locates at the carpal tunnel level. The tendons are covered with synovial sheath in this region. Median nerve injury may accompany the tendon injury. Functional results are successful according to Zone II. However, the risk of adhesion between the tendons, synovial sheath, and median nerve is high in the carpal tunnel.

Zone V: This zone includes the forearm region above the carpal tunnel. Nerve and vascular injuries along with flexor tendons are also seen. Adhesions are usually seen between the tendon and fascia/skin.

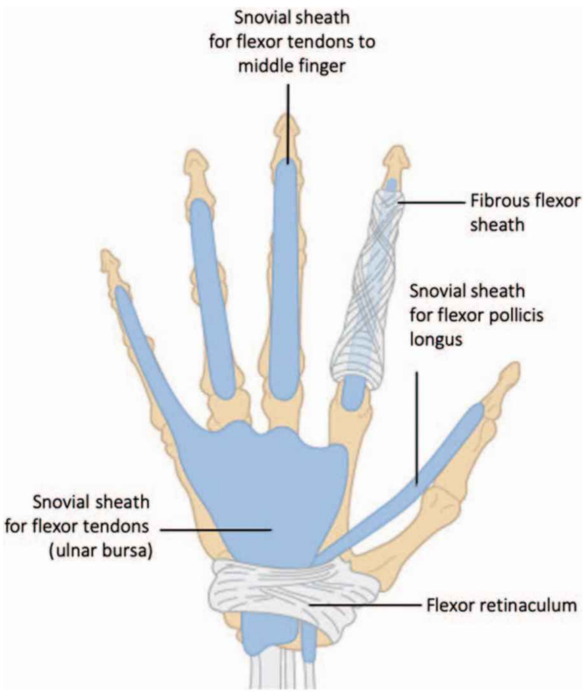

Snovial sheath for flexor tendons to middle finger
Fibrous flexor sheath
Snovial sheath for flexor pollicis longus
Snovial sheath for flexor tendons (ulnar bursa)
Flexor retinaculum

FIGURE 13.89 Arrangement of synovial sheaths for the flexor tendons (Jacob, 2007).

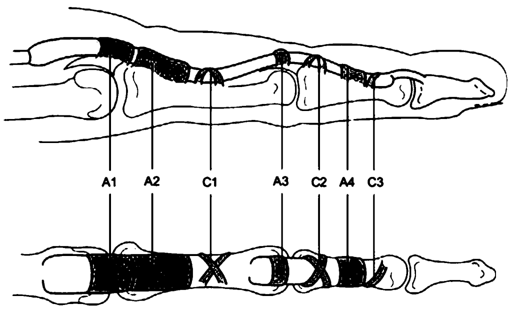


FIGURE 13.90 The digital pulley system includes five annular pulley (A1–A5) and three cruciform pulleys (C1–C3) (Eastman et al., 2008).

Digital flexor sheath and pulley system

The flexor tendons are covered by a flexor synovial sheath, which facilitates tendon gliding and tendon nutrition by diffusion (Fig. 13.89). It is a closed synovial system composed of membranous and retinacular portions (Zafonte et al., 2014).

The membranous portion is composed of visceral and parietal layers. The retinacular component consists of a series of pulleys arranged in cruciform and annular patterns that overlie the membranous portion (Fig. 13.90). The flexor tendon sheaths work in conjunction with the pulley system. The flexor tendons enter this synovium-lined fibro-osseous tunnel at the base of each digit. Pulleys provide a biomechanical advantage by maintaining the flexor tendons in constant relationship to the joint axes, which helps to maximize the efficiency of joint rotation in flexion and force transmission during grip. Pulley system is composed of the transverse carpal ligament, the palmar aponeurosis pulley, and the digital flexor pulley system, which includes five annular pulley (A1–A5) and three cruciform pulleys (C1–C3) (Fig. 13.90), (Manske and Lesker, 1983).

Palmar aponeurosis pulley

The PA pulley consists of transverse fascicular fibers and paratendinous bands of the palmar aponeurosis. The transverse fibers of the palmar aponeurosis are attached by vertical septa to the deep transverse metacarpal ligament beneath the tendons and thus form a tunnel around the flexor tendon and appear to function as a palmar aponeurosis pulley (Doyle, 1990). The proximal margin of the PA pulley is 1–3 mm proximal to the origin of the flexor tendon sheath. The distal margin lies approximately 8–10 mm from the proximal edge of the A1 pulley. The PA pulley functions in conjunction with the first and second annular pulleys of the digital flexor mechanism (Manske and Lesker, 1983). This pulley is not as closely attached to the surface of the flexor tendons as the digital flexor pulleys. However, during grasping, increased tension on the palmar fascia by the FCU and PL muscles moves the pulley closer to the tendon surface.

Mechanical analysis of the palmar aponeurosis

Phillips and Mass (1996) showed that sectioning the palmar aponeurosis pulley alone did not significantly change any of the tendon excursion and work efficiencies. When the palmar aponeurosis pulley was sectioned in combination with either or both proximal annular pulleys (A1, A2) it was found that there was a significant decrease in excursion efficiency. Only after all three proximal pulleys were sectioned did the load efficiency increase which may probably be the result of a decrease in friction and counteractive forces generated by the integrated fibers of the intact palmar aponeurosis pulley and the work efficiency decrease significantly which may due not only to an increase in excursion but also to the increased resistance that results from the acute angulation that the tendon must endure as it follows behind the remaining pulleys during flexion. These findings show that the palmar aponeurosis pulley in combination with the proximal annular pulleys acts to decrease the tendency to bowstringing around the MCP joint.

Digital flexor pulleys

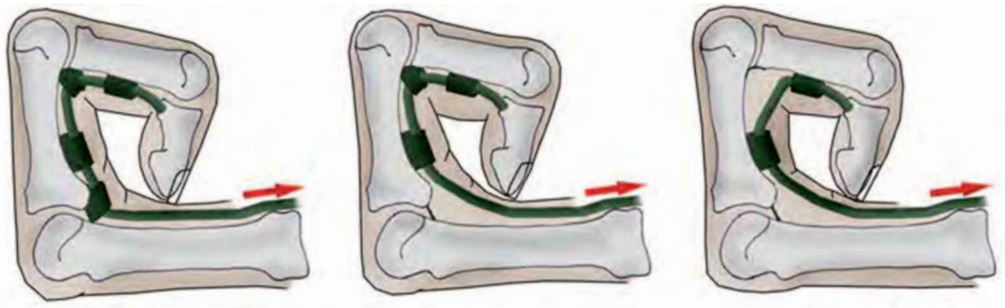
The digital flexor pulleys are the most critical to finger flexion. The annular pulleys are thicker, stronger, and larger fibrous structures. The A1, A3, and A5 pulleys arise from the volar plates of the MCP, PIP, and DIP joints, respectively (Doyle, 1989; Lin et al., 1989; Crowley, 2012). The A2 pulley is continuous with the periosteum of the proximal aspect of the proximal phalanx and A4 pulley is located over the middle third of the middle phalanx, respectively. Of the cruciform pulleys, C1 is located between the A2 and A3 pulleys, C2 between the A3 and A4 pulleys, and C3 between the A4 and A5 pulleys (Boyer et al., 2003).

Larger annular pulleys prevent bowstringing of the flexor tendon during finger flexion, while providing optimal joint function for adequate tendon excursion. Flexor tendon excursion is critical to provide optimal finger flexion during grasping activities. A muscle excursion is directly proportional to muscle fiber length; therefore the maintenance of the relationship between pulleys and the associated joints is critical for the effective tendon excursion (Doyle, 2001). When an annular pulley is injured, the moment arm is increased leading to increased tendon excursion to produce the same amount of motion. The thinner cruciform pulleys provide the flexibility of the flexor sheath and make the flexion movement smoother.

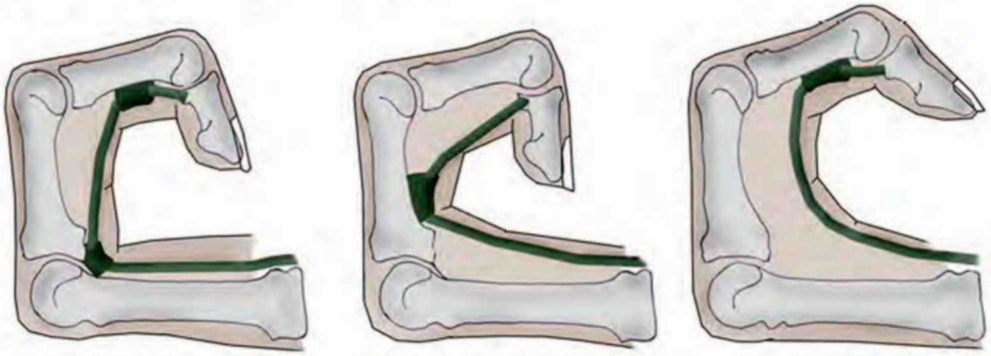
Biomechanical effect of the A2 and A4 pulleys

*A loss of one or several of the flexor tendon pulleys results in bowstringing during finger flexion which leads to decreased tendon excursion and strength and loss of flexion (*Marco et al., 1998*). Many studies investigated the functional importance of the individual flexor tendon pulleys. The A2 and A4 pulleys, which are larger than the others, are found to be the most important ones in preventing bowstringing of the tendon* (Fig. 13.91), (Manske and Lesker, 1977; Bollen, 1990; Marco et al., 1998*).*

Venting the pulleys adversely affects the finger motion depending on the amount of pulley that has been cut (Hamman et al., 1997; Kwai Ben and Elliot, 1998; Mitsionis et al., 1999; Doyle, 2001). The findings demonstrated that a length of 50% of either A2 or A4 pulleys should be maintained for optimal finger kinematics. Anatomic location of pulley venting is another important factor affecting the finger kinematics. Leeflang et al. showed that venting the distal portion of the A2 pulley is showed to result in significantly more bowstringing compared to proximal portion (Leeflang and Coert, 2014). The gliding resistance of the tendon is increased following tendon repairs, which in turn impairs tendon mechanics. Recently, venting and pulley enlargement is recommended to increase free tendon gliding. Venting up to 50% is found to reduce the gliding resistance (Bunata et al., 2011). Therefore the biomechanical effect of flexor pulleys on finger motion is taken into consideration in the operative treatment of the flexor tendon injuries.



A1, A2, A3, and A4 pulleys respected Injury of the A1 pulley Injury of the A1 and A3 pulleys



Injury of the A2 and A3 pulleys Injury of the A1, A3, and A4 pulleys Injury of the A1, A2, and A3 pulleys

FIGURE 13.91 The A2 and A4 pulleys are the most important pulleys in preventing bowstringing of the tendon (Mesplie, 2015).

Thumb flexor tendon sheath

The thumb pulley system is different from the digital pulley system of the other fingers (Doyle and Blythe, 1977). The thumb has a separate flexor tendon sheath. The membranous portion of the sheath arises from the radial styloid and endows the FPL tendon. The retinacular portion consists of one oblique and two annular pulleys overlying the membranous sheath (Fig. 13.92). The first annular pulley (A1) is located at the level of the MCP joint originating from the volar plate and base of the proximal phalanx. The oblique pulley is located at the midportion of the proximal phalanx; the fibers of the pulley extend from the one-third proximal ulnar side of the proximal phalanx to the one-third distal radial side. The second annular pulley (A2) attaches to the volar plate of the IP joint. A1 and oblique pulleys are described as the most important pulleys of the thumb (Zissimos et al., 1994).

Biomechanical properties of flexor tendons

Muscle strength is the tension a muscle can develop and is related to its physiological cross-sectional area and its excursion. Tendon excursion is the distance through which the muscle strength can be produced. Muscle contraction results in joint rotation leading to joint motion. The amount of tendon excursion is related to the amount of joint rotation. The distance that the tendon is from the axis of joint rotation determines the muscle strength provided for the associated joint. A greater moment arm will result in less joint motion, whereas a shorter moment arm will result in more joint rotation. For instance, when the tendon has a greater distance from the axis of joint rotation, which results in increased moment arm, the muscle contraction provided at a given joint will generate less joint motion. Intimate relationship between tendon excursion and joint rotation is maintained by the pulley systems, which keep the tendons close to the related bone. Absent of the digital pulleys may therefore significantly alter the muscle force production and joint motion. Biomechanically, the A2 and the A4 pulleys are the most important for preserving optimal work capacity of the associated muscles. The loss of these pulleys may diminish joint motion and muscle power.

Flexor tendon excursion studies showed that to produce a full range of motion of combined wrist and finger flexion–extension, 9 cm of flexor tendon excursion might be required. It was found that FDS excursion is 49 mm, FDP is 50 mm, and FPL is 35 mm with combined wrist and finger ROM (Wehbe and Hunter, 1985). However, to produce a full finger flexion with the wrist in neutral position 2.5 cm of tendon excursion is required, including 24 mm FDS excursion, 32 mm FDP excursion, and

27 mm FPL excursion (Horibe et al., 1990; Wehbe and Hunter, 1985). McGrouther and Ahmed measured the excursions of the digital flexor tendons relative to the sheath and to one another at a point in Zone II over the proximal phalanx. It was found that DIP joint motion produces excursion of FDP on FDS and a mean of 1 mm of FDP tendon excursion for every 10 degrees of DIP joint flexion is required. PIP joint motion produces excursion of the FDS and FDP together relative to the sheath (1.3 mm for 10 degrees of joint flexion in the index finger) (McGrouther and Ahmed, 1981).

FDS muscle produces less force than the FDP during grasp and pinch. Flexor tendons are subjected 2–4 N of force during unresisted passive flexion. Active flexion with "mild" resistance may result in up to 10 N of force, "moderate" resisted flexion up to 17 N, and strong composite grasp up to 70 N, and firm tip pinch can generate as much as 120 N of tensile load on the index FDP (Schuind et al., 1992; Evans and Thompson, 1993; Greenwald et al., 1994). The forces required to produce full excursion and the work of flexion are increased significantly after flexor tendon repair (Lane et al., 1976; Halikis et al., 1997; Strickland, 2000).

Sapienza et al. investigated the amount of tendon excursion and load experienced during simulated active and passive rehabilitation exercises. Blocking exercises are found to place the highest loads on the flexor tendons. Active motion resulted in higher tendon excursion than did passive motion. Simulated hook position resulted in the highest total tendon excursion and the highest intertendinous excursion.

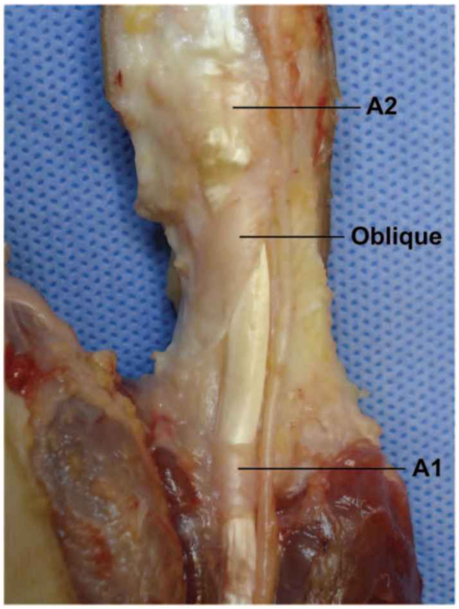


FIGURE 13.92 The flexor pulley system of the thumb (Schubert et al., 2012).

Extensor system

The extensor tendons at the level of the wrist form six extensor compartments as they pass under the extensor retinaculum (Fig. 13.93). These compartments prevent bowstringing of the extensor tendons. Various tendon pathologies can occur in the associated compartments (Table 13.3).

Extensor zones

The extensor tendons are weaker than the flexor tendons and have less working capacity and tendon excursion. The extensor tendons were separated into eight zones according to Kleinert and Verdan (1983) classification system (Fig. 13.94). The eight zones include four odd numbered zones overlying each of the joints and four even numbered zones overlying the intervening tendon segments. Zone I refers to the area from the DIP joint to the fingertip; Zone II refers to the middle phalanx; Zone III refers to the PIP joint; Zone IV is refers to the proximal phalanx; Zone V refers to the MP joint; Zone VI

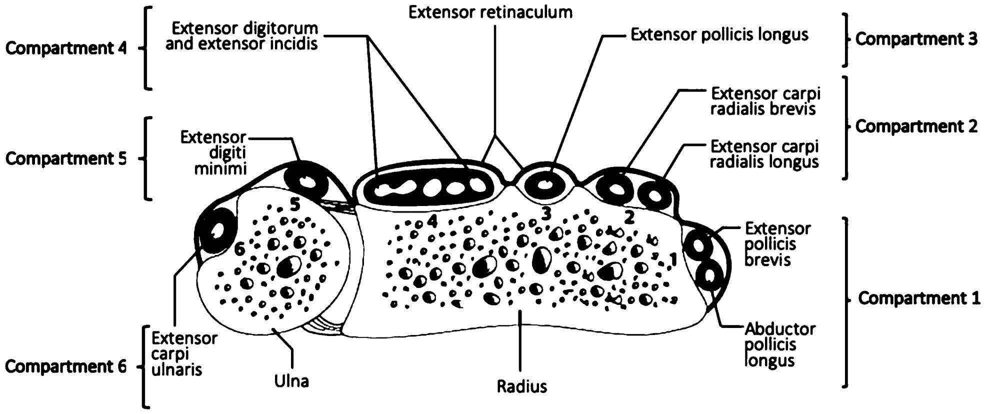


FIGURE 13.93 Extensor compartments at the level of the wrist (Weinzweig, 2010).

TABLE 13.3 Extensor tendon compartments and possible pathologies seen in the relevant compartment.

Compartment	Tendons	Pathology
First	Extensor pollicis brevis Abductor pollicis longus	De Quervain's tenosynovitis
Second	Extensor carpi radialis longus Extensor carpi radialis brevis	Intersection syndrome
Third	Extensor pollicis longus	Rupture following distal radius fracture
Fourth	Extensor digitorum communis Extensor indicis proprius	Extensor tenosynovitis
Fifth	Extensor digiti minimi	Rupture due to rheumatoid arthritis
Sixth	Extensor carpi ulnaris	Extensor tendinitis, ECU subluxation

ECU, Extensor carpi ulnaris.

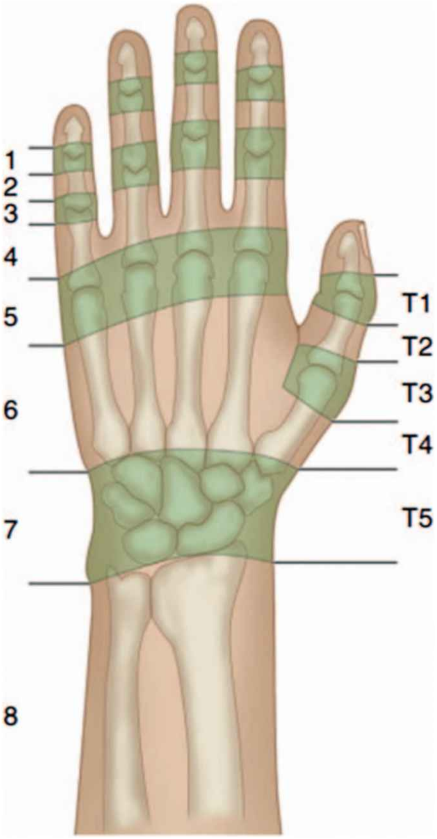


FIGURE 13.94 Extensor tendon zones (Saunders et al., 2016).

encompasses the metacarpal, and Zone VII is over the wrist (Griffin et al., 2012).

Muscles

The extensor system of the hand consists of the extrinsic extensor muscles, including EDC, EIP, EDM, EPL, and brevis (Fig. 13.95). The intrinsic muscles, including palmar and dorsal interosseous muscles and lumbrical muscles, contribute to finger extension. The lumbrical muscles contribute to the flexion of the MCP joints and to the extension of the IP joints via lateral bands. The interosseous muscles abduct and adduct the fingers and contribute the extension of the IP joints via lateral bands. Forearm extensor muscles and the intrinsic muscles work together to provide for optimal digital extension.

Extensor digitorum communis

The EDC muscle is located in the dorsal muscle compartment. The muscle originates from the lateral epicondyle of the humerus and insert to the second–fifth phalanges. The PIN from the radial nerve innervated the muscle. At the proximal two-thirds of the forearm, four separate tendons are formed. The tendons run under the extensor retinaculum at the level of the wrist. The EDC tendons and the EIP tendon form the fourth extensor compartment.

When the tendons exit the retinaculum, the tendons divers on the dorsum of the hand via juncture tendinum which consist of connective tissue slips extending between the EDC, EDM and EIP tendons (Fig. 13.96). Since this structure interconnects the EDC tendons, it is concluded that it plays role in maintaining the space between the tendons, coordination of extension, and redistribution of the force. They are the secondary stabilizer of the EDC at the MCP joint. These structures prevent independent extension of the digits. When MCP joints flexed, it is difficult to extend a digit while the others stay in flexion. However, the second and the fifth digit may independently perform extension via the EIP and EDP tendons, respectively. The juncturae tendinum have a role in stabilizing the EDC tendons at the MCP joints and

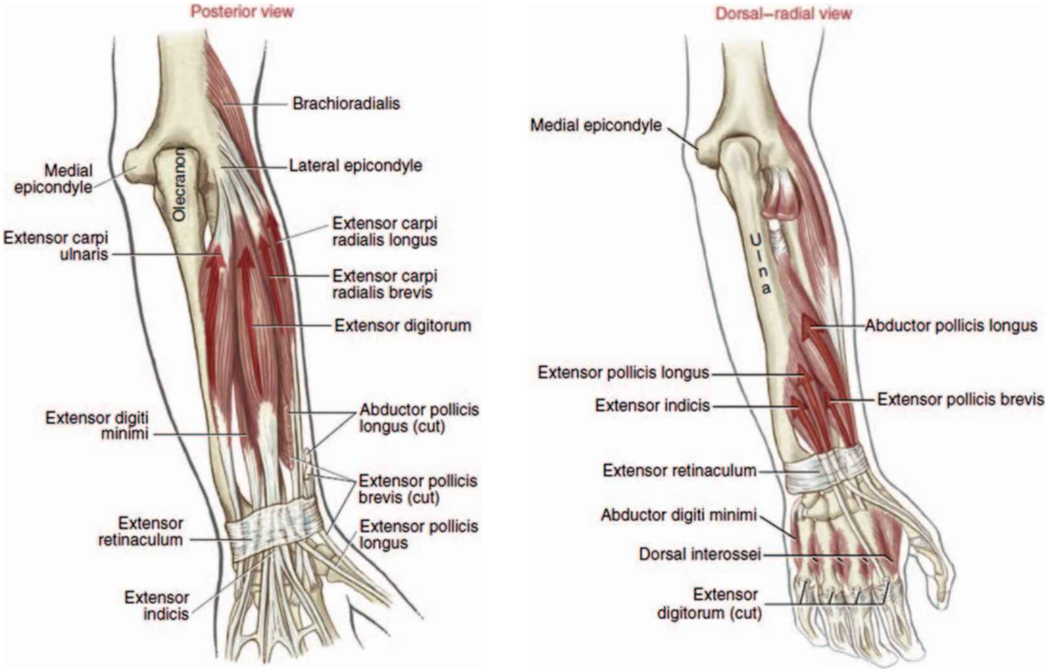


FIGURE 13.95 Extrinsic extensor muscles of the fingers. Extensor digitorum communis, extensor indicis proprius, extensor digiti minimi, extensor pollicis longus, and brevis (Mansfield, 2018).

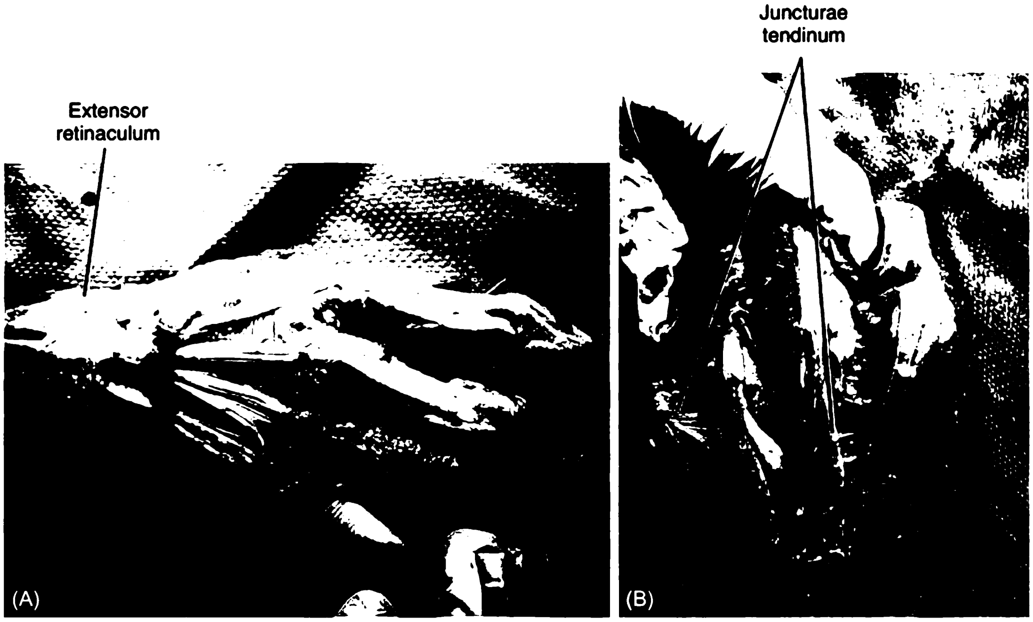


FIGURE 13.96 (A) Cadaver dissection showing extrinsic extensor tendon anatomy of the hand, (B) juncturae tendinum extends between the EDC, EDM and EIP tendons (Saunders et al., 2016).

preventing radial subluxation after ulnar sagittal band rupture. Complete sectioning of the juncturae may lead to subluxation of the EDC tendon over the MCP joint (von Schroeder et al., 1990; von Schroeder and Botte, 1993; Farrar and Kundra, 2012).

The EDC tendons run distally along the phalanges and form the extensor mechanism of each digit. The EDC tendons insert into the base of each middle phalanx through the central slip and into the base of each distal phalanx through the terminal tendon.

Juncture tendinum in extensor tendon injuries

*The juncture tendinum prevent independent digital extension. Therefore they may mask tendon lacerations. These structures gain importance in Zone V–VI injuries. If the extensor tendon injury occurs above the juncture, the adjacent digit is also splinted to prevent excessive tension on the injured tendon when the adjacent digits move from extension to flexion (*Colzani et al., 2016*).*

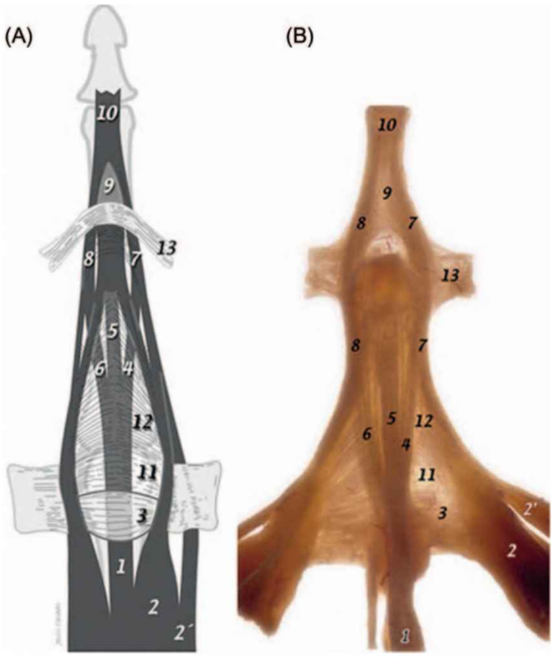


FIGURE 13.97 (A) Drawing and (B) transilluminated anatomic specimen (dorsal view) show the extensor apparatus of the index finger *1* = extensor digitorum tendon, *2* = interosseous muscle, *2′* = lumbrical muscle, *3* = sagittal band, *4* = medial slip, *5* = central slip, *6* = lateral slip, *7* = medial conjoined tendon, *8* = lateral conjoined tendon, *9* = triangular ligament, *10* = terminal tendon, *11* = transverse fibers, *12* = oblique fibers, *13* = retinacular ligament (Hirt et al., 2017; Hirth et al., 2017).

Extensor mechanism

The extensor mechanism is also referred to as extensor aponeurosis, dorsal aponeurosis, or extensor expansion. It is a complex mechanism including intrinsic muscles as well. The EDC tendon is enveloped by the sagittal bands at the level of the MCP joint (Fig. 13.97). Sagittal bands attach to the volar plate and IML. They are the primary stabilizer of the EDC at the MCP joint. They centralize and stabilize the EDC tendons over the metacarpals. During MCP flexion, they resist ulnar deviation of the tendons, and during MCP hyperextension, they prevent bowstringing of the tendon (Young and Rayan, 2000; Marshall et al., 2018). Sagittal bands limit proximal excursion of the EDC tendon, which help to extend the IP joints with the remaining tendon excursion (Clavero et al., 2003). The EDC tendons of each digit run distally and divide into a central slip and lateral bands at the level of proximal phalanx (Fig. 13.97). The central slip inserts on the base of the middle phalanx. A portion of the lateral bands joins with the central slip, which helps PIP extension (Fig. 13.98), (Wehbe, 1995; von Schroeder and Botte, 2001).

Sagittal band injury

At the MCP joint the extensor tendons are stabilized primarily by the sagittal band. Sagittal band injury usually occurs following compressive trauma. Sagittal band

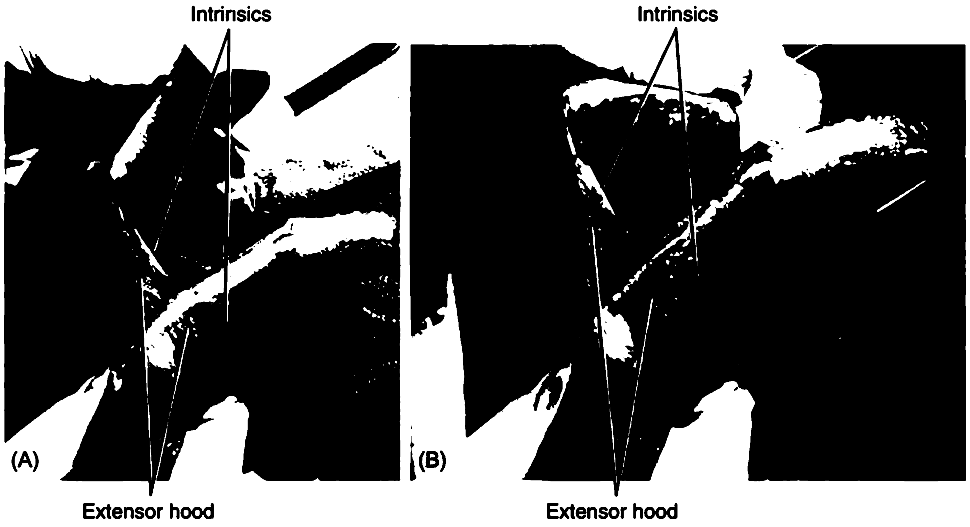


FIGURE 13.98 Orientation of extensor hood and intrinsic contribution to the tendons of the extensor digitorum communis. (A) During extension and (B) during flexion (Saunders et al., 2016).

rupture leads to subluxation or dislocation of the extensor tendon, and it often requires operative stabilization (Fig. 13.99). *The tendon is dislocated when the fingers move from extension to flexion. The radial sagittal band of the third digit is injured most commonly. Complete sectioning of the radial sagittal band ruptures leads to extensor tendon dislocation whereas an ulnar sagittal band rupture does not lead to dislocation. Acute, nonopen injuries are treated with conservative management, which includes extensor tendons splint allowing 30 degree MCP flexion (*Koniuch et al., 1987; Kleinhenz and Adams, 2015*).*

Lateral bands join with the transvers and oblique fibers of the interosseous and lumbrical muscles (intrinsic tendons) over the midportion of proximal phalanx and form the conjoined lateral bands (Fig. 13.100). The conjoined lateral bands run distally with the lateral fibers from the central tendon and continue as a single terminal tendon over the middle phalanx inserting onto the base of the distal phalanx.

The extrinsic extensor tendons primarily extend the MCP joints. They can extend the IP joints when the hyperextension of the MCP joint is prevented. The intrinsic tendons flex the MCP joint and extend the IP joints. The intrinsic tendons lie volar to the axis of motion of the MCP joint. When they form the conjoined tendon at the level of midportion of proximal phalanx they continue dorsally. At the level of PIP and DIP joints, they lie dorsal to the axis of motion. The lateral bands lie dorsally during extension, but they shift volarly during flexion. This shift allows synchronized motion of the PIP and DIP joints (Smith, 1974). Lateral bands are relaxed when the PIP joint is positioned in fully flexion. Therefore they cannot extend the DIP joint in this position. The lateral bands can transfer tension when the PIP joint flexed about 30–40 degrees.

Retinacular ligaments

Retinacular ligaments consist of transverse retinacular ligament, triangular retinacular ligament, and oblique

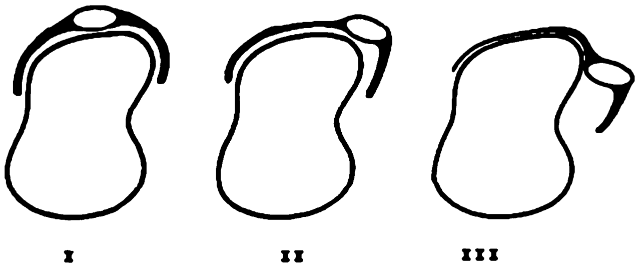


FIGURE 13.99 Three types of sagittal band injury. Type I, mild injury with no instability; type II, moderate injury with extensor tendon subluxation; type III, severe injury with tendon dislocation (Rayan and Murray, 1994).

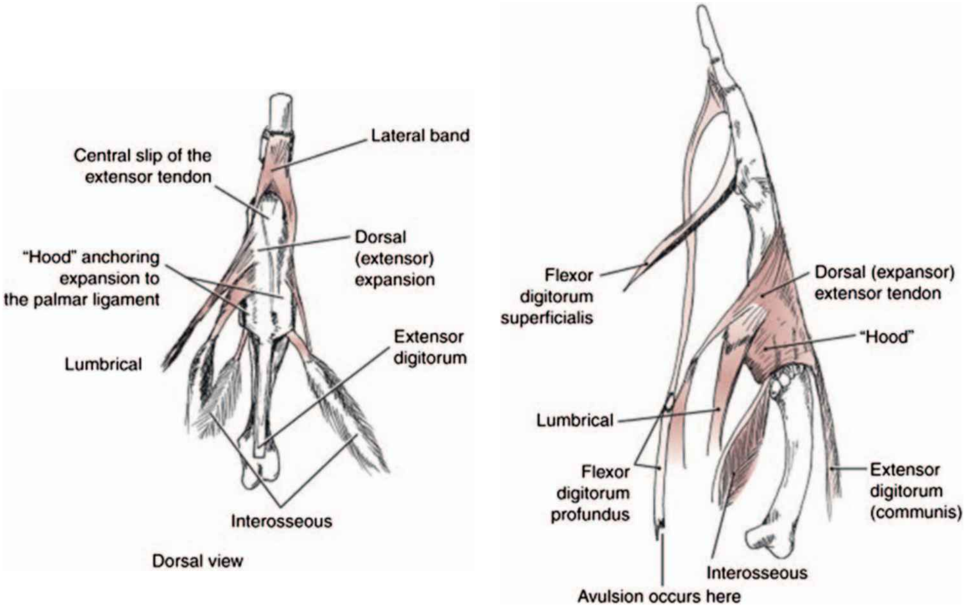

Central slip of the extensor tendon
Lateral band
Dorsal (extensor) expansion
"Hood" anchoring expansion to the palmar ligament
Extensor digitorum
Lumbrical
Interosseous
Dorsal view
Flexor digitorum superficialis
Dorsal (expansor) extensor tendon
"Hood"
Lumbrical
Flexor digitorum profundus
Extensor digitorum (communis)
Interosseous
Avulsion occurs here

FIGURE 13.100 The transvers and oblique fibers of the intrinsic muscles contribute to the EDC tendon (Ballweg et al., 2008). *EDC*, Extensor digitorum communis.

retinacular ligament (ORL) (Fig. 13.101). Transverse retinacular ligament originate from the flexor fibro-osseous sheath and volar plate and runs dorsally over the PIP joint. It covers the joint and provides axial stability to the joint. Like the sagittal bands, the transverse retinacular ligament prevents dorsal displacement of the lateral bands. Besides, it helps volar shifting of the lateral bands during flexion. The distal fibers of the transverse retinacular ligament form the triangular ligament, which connects the conjoined lateral bands. Sectioning of the transvers retinacular ligament will lead to dorsal shift of the lateral bands with development of a swan neck deformity (Mackin, 2002).

The ORL originates from the fibro-osseous sheath at the level of proximal phalanx (Fig. 13.102). It lies palmar to the axis of motion of the PIP joint. It runs dorsally and inserts dorsal base of the distal phalanx. The distal fibers of the ORL converge with the terminal tendon before attaching to the distal phalanx. Landsmeer proposed that DIP extension occurs by the action of the lateral conjoined tendon and by the dynamic IP tenodesis effect exerted by the ORL (Landsmeer, 1963). The ORL assists DIP extension when it is placed under tension via the terminal tendon. The extension of the PIP joint infers extension of the DIP joint (Fig. 13.103), (Adkinson et al., 2014).

The terminal tendon extends the DIP joint into full extension. The terminal tendon injury will lead the loss of 0 degree extension of the DIP joint. Stack (1963) suggested that the ORL extends the DIP joint from full flexion to 45 degrees of extension. The ORL elongate up to 45 degrees when the PIP joint is held in extension. The ORL becomes taut in this position. The passive tension exerted by the ORL ligament, dorsal capsule and collateral ligaments brings the DIP joint to the mid-flexion following terminal tendon injury (Bendz, 1985).

Swan neck deformity

*Swan neck deformity can occur under various conditions, including Zone I extensor tendon injury (mallet finger), FDS minus, volar plate injury of the PIP joint, and tightness of the intrinsic muscles (*Fig. 13.104*). Injury to the terminal tendon (Zone I) at the level of the DIP joint results in mallet finger (*Fig. 13.105*). The extension of the DIP joint is lost. The extension loss of the DIP joint*

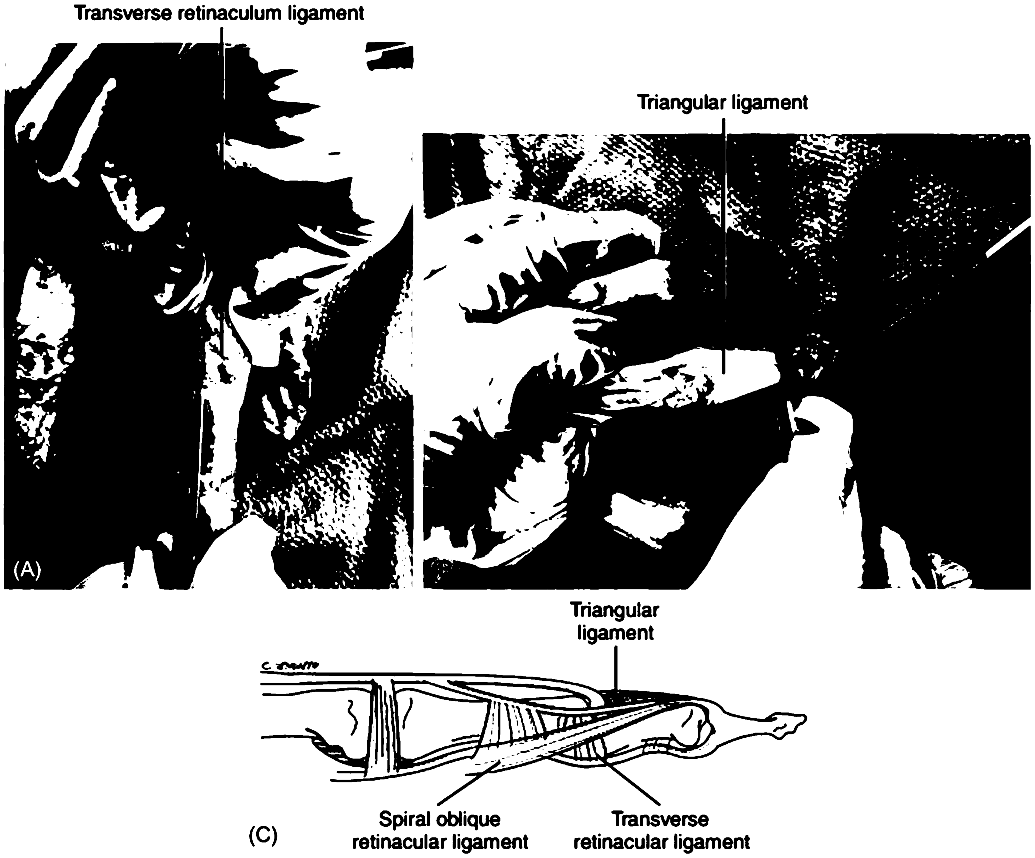

Transverse retinaculum ligament
Triangular ligament
(A)
Triangular ligament
Spiral oblique retinacular ligament
Transverse retinacular ligament
(C)

FIGURE 13.101 (A) Transverse retinacular ligament on the conjoined lateral bands on the volar aspect. (B) Orientation of the triangular ligament linking the conjoined lateral bands dorsally. (C) Arrangement of the transverse retinacular ligament, triangular ligament, and spiral oblique retinacular ligament (Saunders et al., 2016).

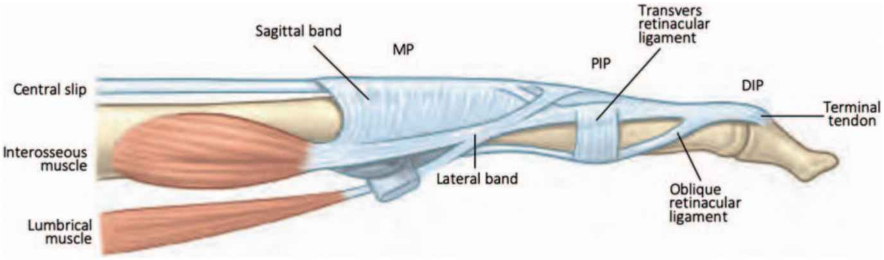


FIGURE 13.102 Oblique retinacular ligament (Standring, 2016).

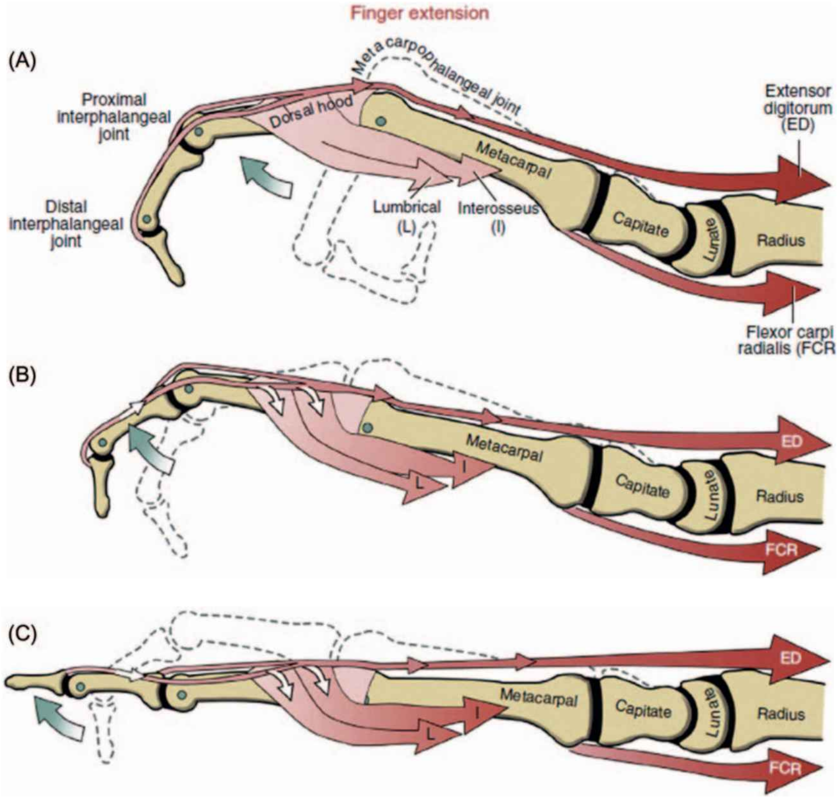


FIGURE 13.103 Lateral view of intrinsic and extrinsic muscular interactions at one finger during opening of the hand. The dotted outlines depict starting positions. (A) Early phase: The extensor digitorum is shown extending primarily the MCP joint. (B) Middle phase: The intrinsic muscles (lumbricals and interossei) assist the extensor digitorum with extension of the proximal and distal interphalangeal joints. The intrinsic muscles also produce a flexion torque at the MCP joint that prevents the extensor digitorum from hyperextending the MCP joint. (C) Late phase: Muscle activation continues through full finger extension (the intensity of the red indicates the relative intensity of the muscle activity) (Mansfield, 2018). *MCP*, metacarpophalangeal.

*transfers the extension forces to the lateral conjoined tendon and the central tendon. The lateral conjoined tendon transfers this force on the middle phalanx via the transverse retinacular ligament. The FDP muscle flexes the DIP joint. The concentrated extension forces lead hyperextension tendency at the PIP joint. The volar plate resists the hyperextension of the PIP joint. When the volar plate is lax, hyperextension develops at the PIP joint. The flexion of the DIP joint with the hyperextension of the PIP joint is called swan neck deformity. Severity of the deformity is proportional to the laxity of the volar plate of the PIP joint (*McKeon and Lee, 2015; Chiu et al., 2017; Ridley et al., 2018*). Among common causes of swan neck deformity are mallet finger, volar plate injury, FDS minus, and intrinsic tightness.*

The closed injuries are treated with continuous immobilization of the DIP joint in neutral extension for 6 weeks with the PIP joint free. When the DIP joint is

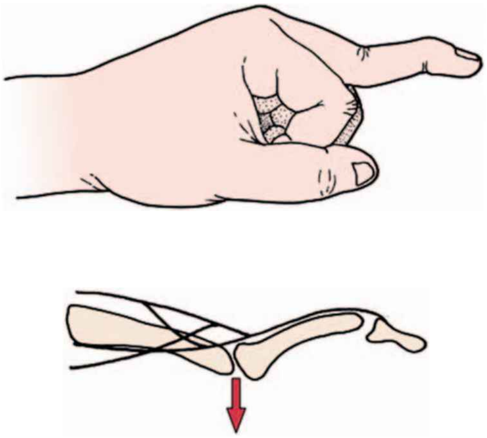


FIGURE 13.104 Swan neck deformity (Magee et al., 2016).

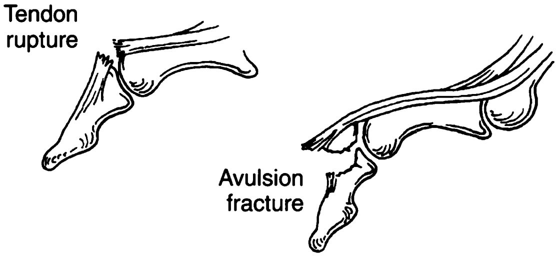


FIGURE 13.105 Zone I extensor tendon injury (Saunders et al., 2016).

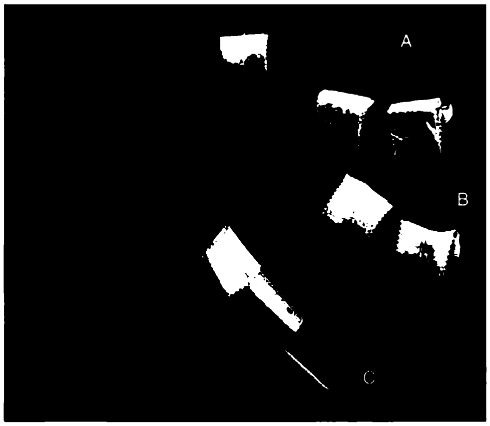


FIGURE 13.106 DIP joint is immobilized in extension following Zone 1 injuries (Saunders et al., 2016). *DIP*, Distal interphalangeal.

FIGURE 13.107 PIP flexion exercise is important to prevent the shortening of the ORL (Seidenberg and Beutler, 2008). *ORL*, Oblique retinacular ligament; *PIP*, proximal interphalangeal.

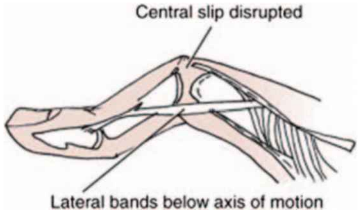


FIGURE 13.108 The disruption of the central tendon (Ballweg et al., 2008).

immobilized in hyperextension, the ORL shortens and leads to flexion limitation of the DIP joint. Therefore neutral extension should be maintained throughout the immobilization period (Fig. 13.106). PIP flexion exercise is important to prevent the shortening of the ORL during the immobilization period (Fig. 13.107).

Boutonniere deformity

*The boutonniere deformity develops following an injury to the central tendon (*Fig. 13.108*). The central tendon is capable of initiation of the extension of the flexed PIP joint and the active terminal extension of 15–20 degrees. This can be tested clinically by actively extending the fingers while positioning the MCP joint in flexion. The disruption of the central tendon impairs the active extension of the PIP joint transferring the extension forces proximally over the middle phalanx through transvers retinacular ligament and over the distal phalanx through lateral bands, the conjoined lateral tendons, and the terminal tendon. The flexion of the PIP joint with the extension of the DIP joint is called boutonniere deformity (*Mesplie, 2015; Binstead and Hatcher, 2018; Grau et al., 2018*).*

*The closed injuries are treated with continuous immobilization of the PIP joint in extension for 6 weeks with the DIP joint free (*Fig. 13.109*). The DIP flexion exercises are performed during the immobilization period (*Fig. 13.110*).*

Relative motion concept

*The RM concept is introduced by the hand surgeon Merritt et al. for the management of V and VI extensor tendon injuries (*Howell et al., 2005; Merritt, 2014*). The concept depends on unloading the injured/repaired tendon by positioning the neighboring tendons originating from the same muscle such as finger extensor or flexor muscles*

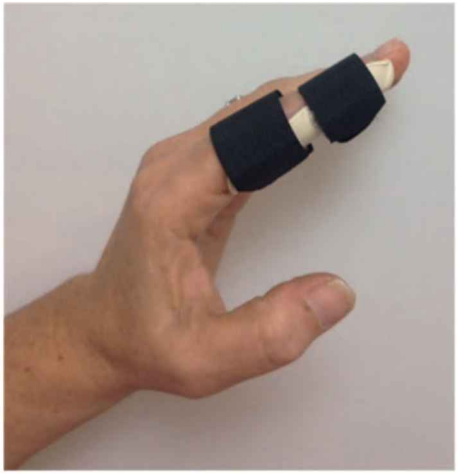


FIGURE 13.109 PIP joint is immobilized in extension following Zone 3 injuries (Magee et al., 2016). *PIP*, Proximal interphalangeal.

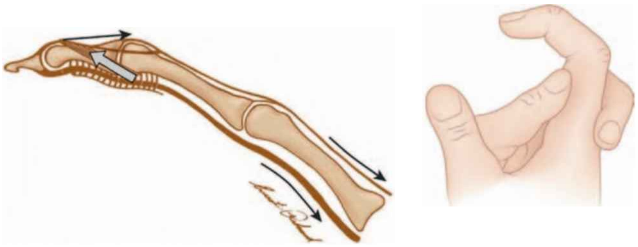


FIGURE 13.110 DIP flexion exercise exerted tension on the lateral bands and the ORL (Magee et al., 2016). *DIP*, Distal interphalangeal; *ORL*, oblique retinacular ligament.

(Fig. 13.111). *Cadaver studies supports the theory of the RM that the strain is decreased on the repaired tendon when using RM splint* (Howell et al., 2005; Sharma et al., 2006). *The RM of the injured tendon is proposed to be 15–20 degrees less than adjacent tendons from same muscle to place less force on the injured tendon. In Zones IV–VII the injured tendon is placed in 15–20 degree greater MCP extension than the adjacent fingers when designing a splint. This is called RM extensor splint. This position is also suggested to decrease the tension following sagittal band injuries* (Merritt et al., 2000).

RM flexor splint is proposed to increase the tension on the extensor hood, which may assist to provide efficient force transmission across the finger (Fig. 13.112), (Merritt, 2014). *It is frequently used following boutonniere deformity. The lumbrical muscles are the primary extensor muscles of the IP joints because the excursion of the lumbrical muscles is four times greater than the excursion of the interosseal muscles* (Paul, 1985). *The lumbricals originate from the FDP tendons, therefore placing the FDP tendons into more relaxed position will also relaxes the lumbrical muscles. Therefore if the injured extensor hood is positioned in 15–20 degree greater MCP flexion than the adjacent fingers, the FDP tendon becomes slack, which in turn places laxity in that lumbrical muscle. This position will increase tension on the extensor hood* (Merritt, 2014).

The effect of the RM concept should be tested clinically when making clinical decision whether the splint will be effective or not. The pencil test is a practical tool to determine the characteristics of the extensor lag (Fig. 13.113).

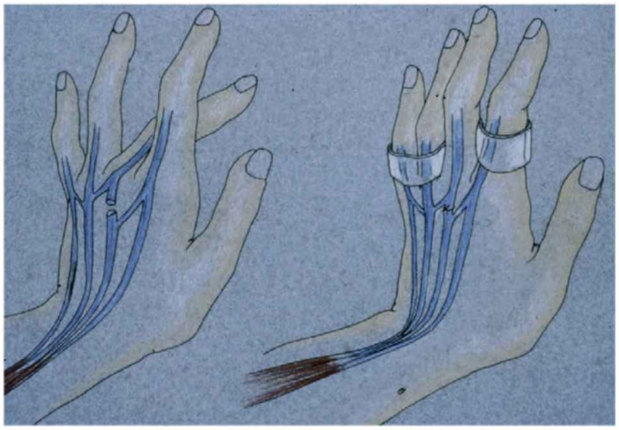


FIGURE 13.111 Relative motion extension splint relaxes the repaired tendon (Merritt, 2014).

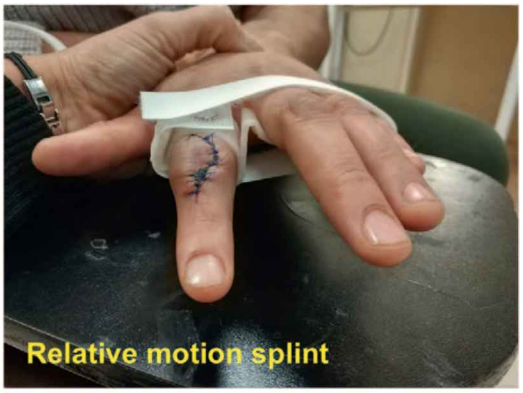


FIGURE 13.112 Relative motion flexor splint to facilitate extensor force transmission across the IP joints. *IP*, Interphalangeal.

Intrinsic muscles

The muscles that arise from the hand and insert on the hand is referred to as intrinsic muscles. The intrinsic muscles involve thenar, hypothenar, palmar, dorsal interossei, and lumbrical muscles. Thenar muscles include OP, APB, AddP, and FPB, and they are described in the previous

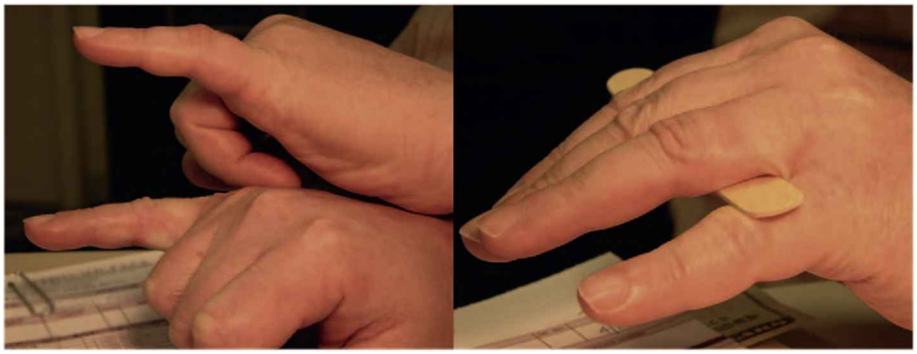


FIGURE 13.113 Positive pencil test for the fifth finger is shown. Blocking the MCP joint in 15 degrees flexion allows active extension of the PIP joint (Merritt, 2014). *MCP*, Metacarpophalangeal; *PIP*, proximal interphalangeal.

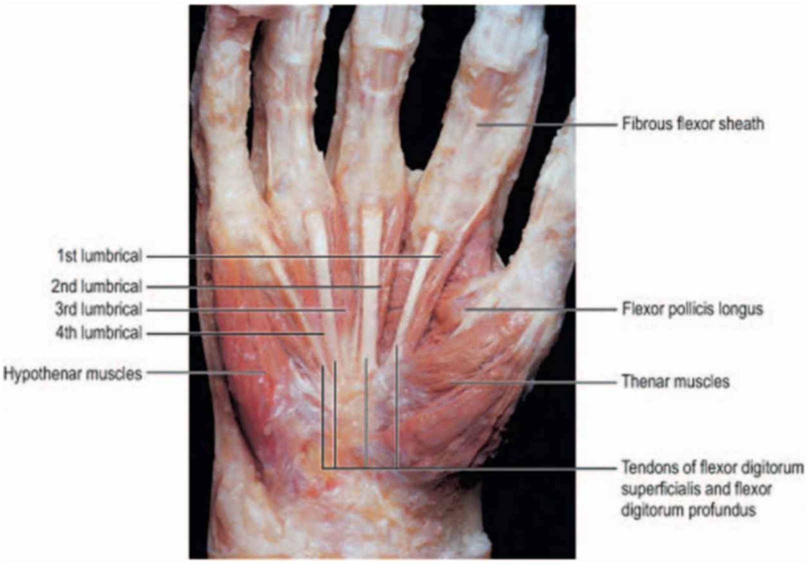


FIGURE 13.114 Anatomy of the lumbrical muscles (Jacob, 2007).

section. Hypothenar muscles include ODM, FDM, and abductor digiti minimi. Although the thenar and hypothenar muscles are intrinsic muscles, the terms, including "intrinsic plus," "intrinsic minus," and "intrinsic tightness," refer only to the interosseal and lumbrical muscles. Interosseal and lumbrical muscles will be discussed in detail because of their substantial biomechanical role in finger motion (Jacobson et al., 1992; Doyle and Botte, 2003).

Lumbrical muscles

Lumbrical muscles arise from the FDP tendons and insert on dorsal surface of the distal phalanx through the lateral conjoined tendons (Fig. 13.114). Lumbrical muscles are unique as they originate from flexor tendons and inserts on the extensor hood. The first and second lumbricals are innervated by the median nerve and the third and fourth are innervated by the deep branch of the ulnar nerve. It is proposed that lumbrical muscles provide substantial proprioceptive information. They are small cylindrical muscles. The first and second lumbricals originate from the radial side of the FDP tendons of the index and long fingers. The third lumbrical originate from the adjacent sides of the FDP tendons of the long and ring fingers. The fourth lumbrical originate from the adjacent sides of the FDP tendons of the ring and small fingers. Each lumbrical muscle passes to the radial side of the corresponding finger. They continue dorsally at the level of MCP joint to join the lateral bands of the extensor hood. The lumbrical muscle is able to relax its own antagonist. The contraction of the FDP relaxes the lumbrical muscles, which allows IP flexion. When the FDP is relaxed, the contraction of the lumbricals pulls the lateral band proximally providing

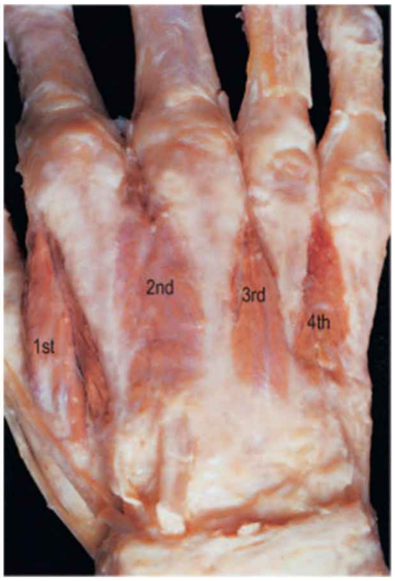


FIGURE 13.115 Anatomy of the dorsal interosseal muscles (Jacob, 2007).

IP extension (Ranney, 1988; Jacobson et al., 1992; Palti and Vigler, 2012; Valenzuela and Varacallo, 2018).

Lumbrical muscles are designed for excursion. Their muscle fibers extend 85%–90% of their muscle length. Since they have small pennation angle and cross-sectional area, they can also produce force. They pass volar to the axis of motion of the MCP joint and dorsal to the axis of motion of the IP joints. The contraction of the lumbrical muscles flexes the MCP joint and simultaneously extends the IP joints. The lumbricals and interosseal muscles work together for this action.

Dorsal interosseal muscles

There are four dorsal interosseal muscles, which are bipennate muscles. They arise from the midshafts of the adjacent sides of the metacarpals and insert into the extensor hood and bases of the proximal phalanx (Fig. 13.115). The first and second interossei insert into the radial side of the base of the proximal phalanx. The third and fourth insert into the ulnar side of the base of the proximal phalanx. The interossei are innervated by the deep branch of the ulnar nerve. The muscles abduct the index, long and ring finger from the mid-axis of the long finger. They also flex the MCP joints and extend the IP joints (Jacobson et al., 1992).

Palmar interosseal muscles

There are three palmar interossei muscles to index, ring, and small finger. They arise from the ulnar (index finger) and radial (ring and small finger) side of the metacarpal palmar to the origin of the dorsal interossei (Fig. 13.116). The muscles insert into the extensor hood of the associated finger. The palmar interossei are innervated by the deep branch of the ulnar nerve. The muscles adduct the index, ring, and small finger toward the mid-axis of the long finger. They also flex the MCP joints and extend the IP joints with working with the dorsal interossei and the lumbricals.

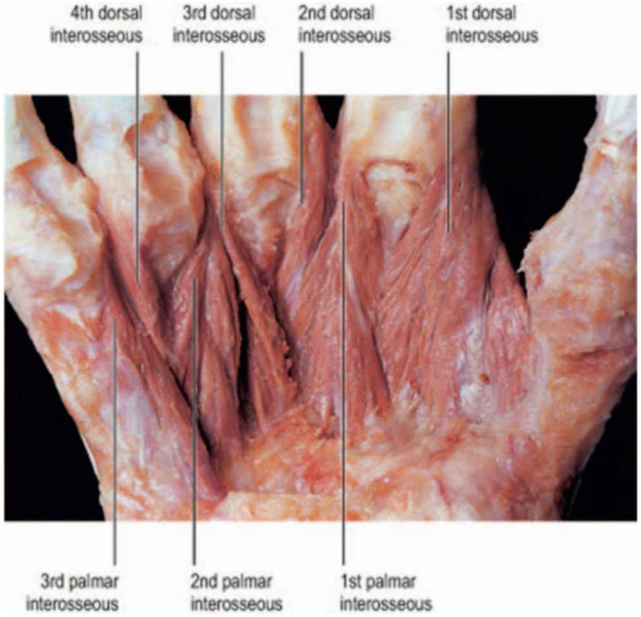


FIGURE 13.116 Anatomy of the palmar interosseal muscles (Jacob, 2007).

The muscle architecture of the dorsal and palmar interossei is similar to the lumbricals. They are designed for excursion. Their fiber length is long and has small cross-sectional area.

Intrinsic muscle test

*Intrinsic muscles are tested in MCP flexion and IP extension (*Fig. 13.117*). Patient positions the MCP in flexion and IP joints in extension, and the examiner then apply external force in the direction of MCP extension and IP flexion. Muscle strength is graded from 0 to 5 (*Brandsma et al., 1995; Schreuders et al., 2006*).*

Intrinsic minus

*Intrinsic muscle paralysis due to ulnar nerve lesion results in a position of MCP extension and IP flexion (*Fig. 13.118*). This position shows that the extrinsic finger flexor and extensor muscles produce movement at MCP and IP joints. The contracture of extrinsic finger flexor and extensors following compartment syndrome may also results in intrinsic minus (*Srinivasan, 1977; Sapienza and Green, 2012*).*

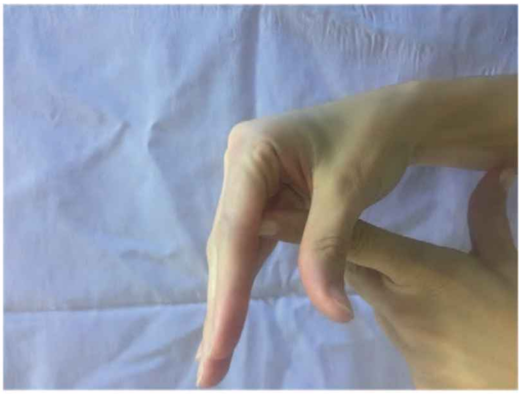


FIGURE 13.117 Intrinsic muscle test.

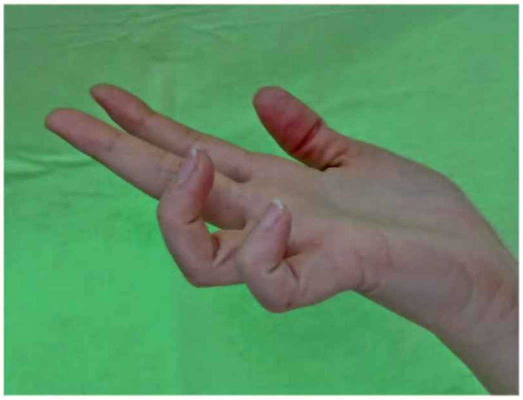


FIGURE 13.118 Intrinsic minus position following ulnar nerve lesion.

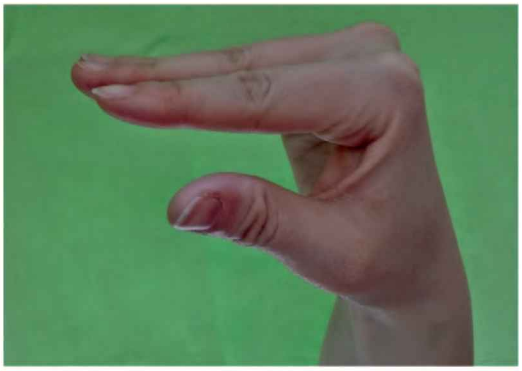


FIGURE 13.119 Intrinsic plus position (right hand) due to spasticity.

Correction of this posture is important for maintaining the optimal length tension relationship of the intrinsic muscles and protecting the metacarpal arch until the intrinsic muscles are reinnervated. Various splints such as knuckle benders can be used to correct this posture. Knuckle benders are practical splints positioning the MCP joints in flexion and IP joints in extension.

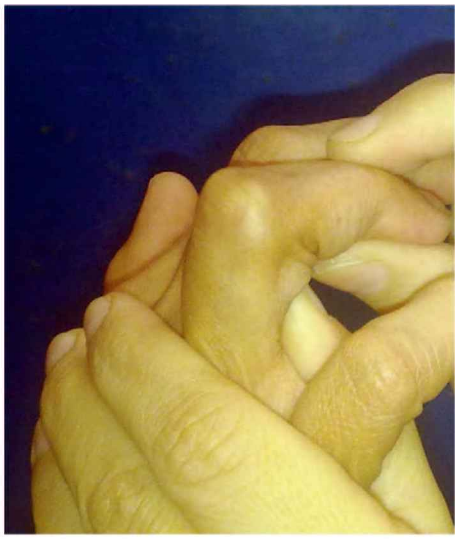


FIGURE 13.120 Bunnell-Littler test for assessing the tightness of the interosseal muscles.

Intrinsic plus position

*Overactivity of the intrinsic muscles due to spasticity or tightness of the intrinsic muscles due to inflammatory conditions such as rheumatoid arthritis or traumatic conditions lead to intrinsic plus position in which the MCP joint is flexed and the IP joints are extended (*Fig. 13.119*).*

*Intrinsic plus position may also cause swan neck deformity depending on the severity of the condition. When the lateral bands displace dorsally, the volar plate of the PIP joint becomes slack over time. Dorsally displaced lateral bands concentrate the extension forces on the PIP joint leading to hyperextension at the joint (*Nakamura et al., 1965; Mackin, 2002; Soeters et al., 2010*).*

Longstanding edema following hand traumas usually results in tightness of the intrinsic muscles. Intrinsic muscle tightness can be assessed clinically with the Bunnell-Littler test (Finochietto test) (Fig. 13.120). However, interosseal and lumbrical muscle tightness tests differ from each other.

The Bunnell-Littler test actually assesses tightness of the interosseal muscles. The examiner positions the MCP joint in extension and passively flexes the PIP joint and records the available ROM. The test is then repeated with the MCP joint in flexion. If the PIP ROM is increased when the MCP joint is positioned in flexion, the tightness of the interosseal muscle is presented.

Since the lumbrical muscles originate from the FDS muscle, passive flexion of the IP joint during Bunnell-Littler test cannot evaluate the tightness of the lumbrical muscles. The lumbrical muscle tightness should be evaluated with active contraction of the FDP muscle (Fig. 13.121). The examiner positions the MCP joints in

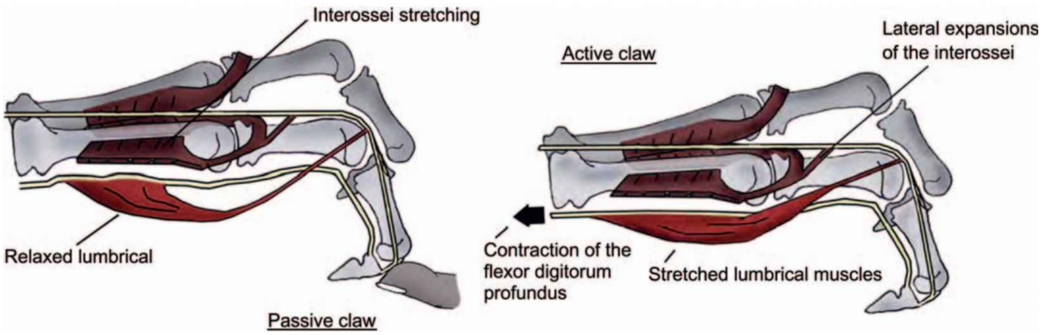


FIGURE 13.121 The mechanisms of the interosseal and lumbrical tightness tests (Mesplie, 2015).

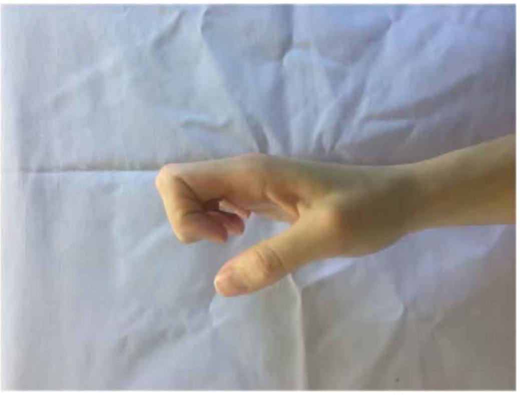


FIGURE 13.122 Lumbrical tightness test.

extension and the patient actively flexes the IP joints. Then the test is repeated in MCP flexion (Fig. 13.122).

Clinical decision-making depends on a comprehensive evaluation of the hand. It is necessary to understand the functional anatomy, biomechanics, and kinesiology of the hand. A finger movement is the result of the delicate coordination between the intrinsic and extrinsic hand muscles. When designing a rehabilitation program, a systematic evaluation of the joints and muscles is paramount to differentiate between the musculoskeletal and joint stiffness. Following descriptions may provide information for clinical decision-making.

- If the AROM and PROM are the same regardless of the position of the proximal joints, the limitation depends on the joint stiffness.
- If passive flexion is greater than active flexion, the limitation is due to tendon adhesion.
- If active and passive flexion is equal and flexion is better when the proximal joints are extended, limitation is due to the tightness/adhesion of the extrinsic extensor tendons.
- If active and passive flexion is equal and extension is better when the proximal joints are flexed, the limitation depends on the tightness/adhesion of the extrinsic flexor tendons.
- If passive flexion of the IP joints increases with joint flexion of the MCP, the limitation depends on the tightness of the intrinsic muscles (interosseal muscles).

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Part 4

Trunk and pelvis

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Chapter 14

Kinesiology of the temporomandibular joint

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Introduction

The stomatognathic system is a complex system that serves the sensory side with functions such as chewing, speech, swallowing, yawning, breathing and mimics. According to the American Academy of Orofacial Pain, the stomatognathic system is, the functional and anatomic relationship among the teeth, jaws, TMJs, and muscle of mastication (de Leew, 2013). There is a physiological harmony between these structures. In addition, the vessels and nervous structures that nourish and constrict these structures and the soft tissues control and coordinate all these structural components (Hylander, 2006; de Leew, 2013).

The temporomandibular joints (TMJ) are the two-condylar joints between the head of the coronoid process of the mandible and the mandibular fossa of the temporal bone (Hylander, 2006; Tanaka and Koolstra, 2008; de Leew, 2013). The TMJs are bilateral, diarthrodial, ginglymoid, synovial, freely movable and are the most used joints in the body during daily function (Tanaka and Koolstra, 2008). There is a structural relationship of the TMJ to the head contributes to the impact on the muscles of the upper quadrant and the cervical spine (Hylander, 2006; Alomar et al., 2007; Tanaka and Koolstra, 2008). The main components are the mandibular fossa, mandibular condyle, articular disc, joint capsule, ligaments, and muscles (Fig. 14.1).

Structure of the temporomandibular joint

Mandibular fossa

The mandibular fossa also referred as the glenoid fossa, is the concavity within the temporal bone that forms the roof of the TMJ (Hylander, 2006; Tanaka and Koolstra, 2008; de Leew, 2013). Anteriorly, the mandibular fossa is bounded by the articular eminence of the squamous temporal bone and posteriorly by the tympanic plate, which also forms the anterior wall of the external acoustic meatus. In the back and lateral part of the mandibular fossa, a fissure, called the tympanosquamous fissure, separates the articular and the nonarticular portions of the mandibular fossa (Tanaka and Koolstra, 2008). The articular fossa is lined with articular tissues, and formed entirely by the squamous portion of the temporal bone.

The fibrous tissue covering the articular eminence is thick and firm. On the other hand, the roof of the mandibular fossa is thin and non-weight-bearing. Loads are born between the mandibular condyle and intraarticular disc and between the disc and articular eminence of the temporal bone (Tanaka et al., 2003; Alomar et al., 2007; Neumann, 2010).

Mandibular condyle

The articular surface of the mandible is the upper and anterior surface of the condyle and forms the floor of the TMJ. The adult condyle is about 15–20 mm mediolaterally and 8–10 mm anterioposteriorly (Alomar et al., 2007). A thin but dense layer of fibrocartilage covers the articular surface of the mandibular condyle (Neumann, 2010). The appearance of the mandibular condyle varies greatly among different age groups and individuals. The condyle is generally convex, possessing short projections known as medial and lateral poles. The lateral pole of the condyle lies anterior to the transverse axis of the condyle, and the medial pole lies posterior to the transverse axis of the condyle (Alomar et al., 2007). The lateral pole of the condyle extends slightly beyond the ramus that can be palpated while the jaw is opening and closing. A line

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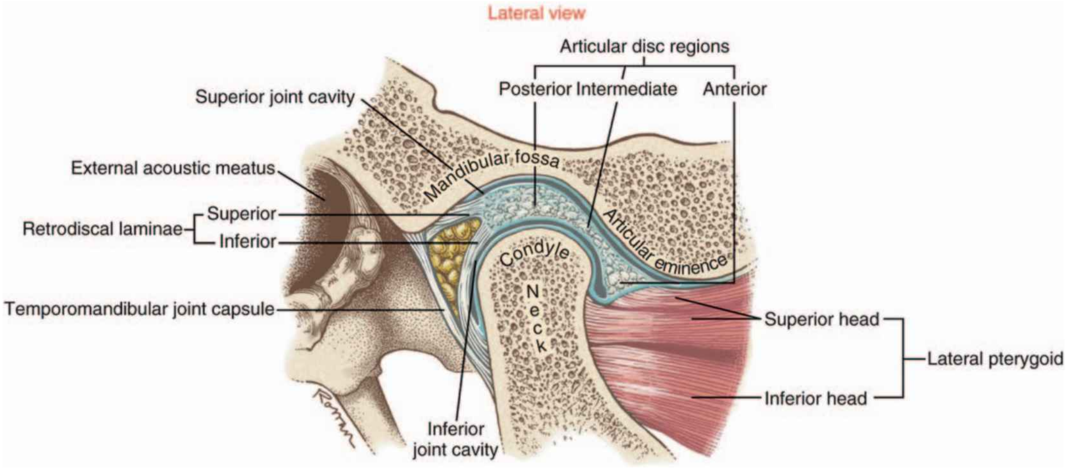

FIGURE 14.1 The Temporomandibular Joint (TMJ)- lateral view.

running between the medial and lateral poles of each condyle is referred to as the long axis of the condyle. Extending the long axis of each condyle medially forms an obtuse angle varying from 145 to 160 degrees, which condyles cross approximately at the anterior margin of the foramen magnum (Alomar et al., 2007; Neumann, 2010).

Articular disc

The articular disc is a biconcave fibrocartilage structure and consists of dense bundles of collagen fibers, and separates the joint into two spaces, which are the inferior and superior compartments (Tanaka et al., 2003; Hylander, 2006). The inferior compartment is between the lower surface of the joint discoid and the mandibular condyle head. The upper compartment is larger than the lower joint space and is between the upper surface of the joint discoid and the mandibular fossa.

The disc can be divided into three parts; anterior band, intermediate zone, and posterior band (Tanaka et al., 2003; Alomar et al., 2007). The anterior band of the disc is generally flat inferiorly, and concave superiorly to accommodate the convexity of the articular eminence, and attaches the anterior capsule of the TMJ, tendon of the superior head of the lateral pterygoid muscle and to the temporal bone just anterior to the articular eminence (Tanaka et al., 2003; Tanaka and van Eijden, 2003). The intermediate zone of the disc is concave inferiorly and flat superiorly and attaches to the medial/lateral poles of the condylar head through the medial/lateral collateral ligaments. The posterior band of the disc is convex superiorly and concave inferiorly and continues as the posterior attachment or bilaminar zone, a thick double layer of vascularized connective tissue (Tanaka et al., 2003; Tanaka and van Eijden, 2003). It is described that the anterior and posterior parts have neural innervations and vascular supply, but the intermediate portion is avascular and aneural. The intermediate portion is the thinnest area, and receives its nutrition from the synovial fluid (Tanaka and van Eijden, 2003; Tanaka et al., 2008a,b; Neumann, 2010; Okeson, 2013). The disc filled with synovial fluids maintains the lubrication of the TMJ to the articulating surfaces, transmits contact force, guides the condyle during movements, stabilizes the joint, and endures long-term stress (Tanaka and van Eijden, 2003; Tanaka et al., 2008a,b).

The function of the disc is to board a rotating action as well as the translation action between the temporal and mandibular articular bone. Rotation or hinge movements occur in the inferior compartment, while translation movements occur primarily in the superior compartment (Tanaka and Koolstra, 2008; Neumann, 2010; Okeson, 2013). The biconcave shape of the disc is determined by the morphology of the condyle and the mandibular fossa. In maximal intercuspation, the intermediate region of a healthy disc should fit between the condyle of mandibular and the articular eminence of the fossa (Tanaka and van Eijden, 2003). During movement, the disc is flexible and can adapt to the functional demands of the articular surfaces, and because of its viscoelastic possessions, can behave as stress absorber and distributor (Tanaka et al., 2003; Tanaka and van Eijden, 2003; Manfredini, 2009). These functions protect the joint from degeneration of the disc.

Capsules

The joint capsule is a thin fibroelastic, highly vascular and innervated dense connective tissue (Hylander, 2006; Alomar et al., 2007; Tanaka and Koolstra, 2008) that originates from the border of the mandibular fossa encloses the articular tubercle of the temporal bone and inserts at the neck of mandible above the pterygoid fovea. Anteriorly, the capsule blends with the superior head of the lateral pterygoid muscle. Posteriorly, the capsule attaches to the petrotympanic fissure and fuses with the superior stratum of the posterior bilaminar zone. Inferiorly the capsule attaches to the periphery of the articular disc and to the superior neck of the mandible, and superiorly to the rim of the mandibular fossa (Ingawale and Goswami, 2009; Kuroda et al., 2009). Medially and laterally the capsule is relatively firm, providing stability to the joint during lateral movements. However, anteriorly and posteriorly, the capsule is relatively flexible, allowing the condyle and disc to translate during opening (Hylander, 2006; Manfredini, 2009; Neumann, 2010). The functions of the capsule of the TMJ are to resist forces that separates articulating surfaces, provide significant support to the articulation and to the stability of the TMJ (Neumann, 2010; Okeson, 2013).

Ligaments

The fibrous joint capsule thickens medially and laterally is often referred to as the medial collateral and lateral collateral ligaments of the TMJ (Hylander, 2006; Alomar et al., 2007). The collateral ligaments attach to the medial and lateral borders of the disc and insert on the medial and the lateral poles of the condyle, respectively. They are vascularly innervated, and provide information regarding joint position and movement. Their function is to restrict excessive medial and lateral movement of the disc, so the disc moves as a unit in the anterior-posterior direction (Alomar et al., 2007; Manfredini, 2009).

The temporomandibular ligament is the main ligament of the joint, lateral to the capsule therefore often referred as the lateral ligament (Hylander, 2006; Alomar et al., 2007). The ligament has two parts; superficial oblique and deeper horizontal. The superficial oblique fibers of the ligament arise from the lateral surface of the articular tubercle and the zygomatic process and insert on the posterolateral surface of the condylar neck. The deeper horizontal part arises from the same origin and insert on the lateral pole of the condyle. The primary function of the temporomandibular ligament is to stabilize the lateral side of the capsule (Hylander, 2006), limit rotation of the condylar head during jaw opening, and posterior displacement of the condyle, therefore protecting the retrodiscal pad (Ho, 2001; Manfredini, 2009; Neumann, 2010).

Two other ligaments, stylomandibular and sphenomandibular ligaments are considered as the accessory ligaments of the TMJ. The stylomandibular ligament arises from the styloid process of the temporal bone and inserts on the mandibular angle. The sphenomandibular ligament arises from the angular spine of the sphenoid and petrotympanic fissure and then runs downward and outwards to insert on the lingula of the mandible. These ligaments are passive during mandibular movements, maintaining relatively the same degree of tension during both opening and closing of the mouth (Hylander, 2006; Alomar et al., 2007; Neumann, 2010).

Muscles

The muscles of mastication are the paired masseter, the temporalis, the medial pterygoid, and the lateral pterygoid muscles (Hylander, 2006; Oatis, 2009; Okeson, 2013). Mandibular movements are achieved by harmonious contraction and relaxation of all chewing muscles. These muscles of mastication are in conjunction with various muscle groups of face, tongue, palate, and hyoidal muscles during the mastication (Ho, 2001; Manfredini, 2009; Oatis, 2009). Suprahyoidal and infrahyoidal muscles play a role in chewing allowing the mouth to open with mandibular depression, and provide the fixation of the hyoid bone (Table 14.1).

Masseter muscle

The masseter muscle is a strong muscle with superficial and deep heads that functions as one of the major muscles of mastication (Hylander, 2006; Neumann, 2010). Origination of the muscle is at the zygomatic arch and the zygomatic process of maxilla. The superficial head passes inferiorly and posteriorly inserting to the angle of the mandible, whereas the deep head passes downward and forward inserting to the upper half of the ramus of the mandible (Hylander, 2006).

The masseter is a powerful elevator muscle of the mandible providing the necessary force to chew efficiently. Masseter muscle develops necessary forces to grind and crush the food effectively on posterior molars (Neumann, 2010; Okeson, 2013). During the bilateral contraction of the muscle, elevation of the mandible is observed and mandibular jaw closes. In the meanwhile, this bilateral contraction of the superficial heads produces mandibular protrusion, whereas deep heads contribute to retraction of the mandible. On the other hand, action of lateral gliding during the chewing function causes unilateral contraction of the masseter muscle with clinical presentation of ipsilateral excursion of the mandible (Oatis, 2009; Neumann, 2010; Okeson, 2013).

Temporalis muscle

The temporalis is a large muscle originating from the temporal fossa and the lateral surface of the skull (Hylander, 2006). The muscle medially passes the zygomatic arch by narrowing distally and inserts to the inner surface of the coronoid process, upper anterior border and

TABLE 14.1 **Temporomandibular joint - function, muscles and nerve supply.**

Function	Muscles	Nerve supply (cranial nerve: CN)
Elevation (closing)	1. Masseter 2. Temporalis 3. Medial pterygoid 4. Lateral pterygoid superior	1. Mandibular (CN V) 2. Mandibular (CN V) 3. Mandibular (CN V) 4. Mandibular (CN V)
Depression (opening)	1. Digastric 2. Mylohyoid 3. Geniohyoid 4. Lateral pterygoid inferior	1. Mandibular (CN V) and Facial (CN VII). Facial (CN VII) 2. Mandibular (CN V) 3. Hypoglossal (CN XII) 4. Mandibular (CN V)
Protrusion	1. Lateral pterygoid inferior 2. Medial Pterygoid 3. Masseter superficial 4. Temporalis anterior	1. Mandibular (CN V) 2. Mandibular (CN V) 3. Mandibular (CN V) 4. Mandibular (CN V)
Retraction	1. Temporalis posterior 2. Masseter deep 3. Digastric 4. Lateral pterygoid superior 5. Stylohyoid 6. Mylohyoid 7. Geniohyoid	1. Mandibular (CN V) 2. Mandibular (CN V) 3. Mandibular (CN V) and Facial (CN VII) Facial (CN VII) 4. Mandibular (CN V) 5. Facial (CN VII) 6. Mandibular (CN V) 7. Hypoglossal (CN XII)
Lateral excursion	1. Temporalis ipsilateral 2. Masseter ipsilateral 3. Lateral pterygoid contralateral 4. Medial pterygoid contralateral	1. Mandibular (CN V) 2. Mandibular (CN V) 3. Mandibular (CN V) 4. Mandibular (CN V)

medial border of ramus of mandible (Hylander, 2006; Neumann, 2010).

The temporalis muscle is grouped into three portions due to the function of the muscle and direction of the muscle fibers. The anterior portion consists of vertical fibers. The middle portion contains oblique fibers, which passes through the lateral aspect of the skull. The posterior portion positions horizontally, passing downward vertically to the mandible and bending around the posterior root of the zygomatic arch in front of the articular eminence (Hylander, 2006). Unilateral contraction produces the same side lateral excursion during the side-to-side chewing activity, while bilateral contractions of the temporalis muscle causes elevation of the mandible. The posterior temporalis contraction produces slight retrusion during the mouth closing (Oatis, 2009; Neumann, 2010; Okeson, 2013).

Medial pterygoid muscle

The medial pterygoid muscle is the deepest of the muscles of mastication (Hylander, 2006). The muscle has two heads; superficial and deep parts. The superficial head arises from the maxillary tuberosity and the pyramidal process of the palatine bone, and the deeper head arises from the lateral pterygoid plate of the sphenoid bone. Both heads of the medial pterygoid insert on the medial surface of the mandibular angle. The function of medial pterygoid, while contracting bilaterally, it produces elevation and protrusion of the mandible, while unilaterally contracted, it produces contralateral excursion (Neumann, 2010; Okeson, 2013). It pulls the ramus of the mandible medially and shifting the mandible toward to the contralateral side. In addition, the medial pterygoid along with the masseter muscle, forms a muscular sling that supports the mandible at the mandibular angle and empowers their elevator strength. Simultaneous contractions of these muscles can exert a powerful biting force and mastication (Oatis, 2009; Neumann, 2010; Okeson, 2013).

Lateral pterygoid muscle

The lateral pterygoid muscle arises from two heads, and described as the inferior lateral and the superior lateral pterygoid (McNamara, 1973; Hylander, 2006).

The inferior head is about three times larger than the superior head and their functions are nearly opposite. The inferior lateral pterygoid arises from the lateral border of the lateral pterygoid plate and inserts to the pterygoid fovea on the neck of the mandible, and the superior lateral pterygoid arises at the infratemporal surface of the greater sphenoid wing of the sphenoid bone, and inserts on the articular capsule, the disc, and the neck of the condyle (McNamara, 1973; Wood et al., 1986).

There are some controversies regarding the percentage of insertion fibers of the superior head of the disc (McNamara, 1973; Wood et al., 1986; Wilkinson, 1988; Murray et al., 2001). Unilateral contraction of the lateral pterygoid muscle produces contralateral excursion of the mandible and ipsilateral rotation of the condyle anterior-medially within the horizontal plane (Murray et al., 2001). Bilateral contraction of both heads of the lateral pterygoid muscle produces a strong protrusion of the mandible (Murray et al., 2001; Kuroda et al., 2009). Most of the researchers believe the function of the superior head of the lateral pterygoid that due to its connection to the disc (Wilkinson, 1988), the muscle contracts eccentrically during mouth closing to control the disc position and avoids displacement and stabilizes the disc during mandibular function.

Suprahyoidal muscles

The suprahyoid muscles include the digastric, mylohyoid, geniohyoid, and stylohyoid muscles (Palmer et al., 1992; Sataloff et al., 2007; Hannam et al., 2008). All suprahyoid muscles bring to elevate the hyoid bone, and alternatively when the hyoid bone is fixed, the suprahyoid muscles are responsible for mandibular depression and retrusion of the mandible during opening of the mouth (Palmer et al., 1992). They also play a role in chewing, and swallowing (Palmer et al., 1992; Naeije and Hofman, 2003; Sataloff et al., 2007). The digastric and mylohyoid muscles can elevate the hyoid, the tongue, and floor of the mouth. This is important during swallowing and speaking. Alternatively, if other muscles are used to keep the position of the hyoid fixed, then the mylohyoid depresses the mandible. The geniohyoid muscle brings the hyoid bone forward and upwards. It also assists in depressing the mandible. The stylohyoid muscle, when contracted, is believed that the muscle functions as a stabilizer, retractor, and elevator of the hyoid bone (Palmer et al., 1992; Sataloff et al., 2007). If the suprahyoid and infrahyoid muscles fix the hyoid bone, it will tend to depress the mandible; when the mandible is stabilized, the muscles elevate the hyoid bone, which is a necessary function for swallowing (Naeije and Hofman, 2003; Sataloff et al., 2007).

Infrahyoidal muscles

The infrahyoid muscles include thyrohyoid, sternothyroid, sternohyoid, and omohyoid (Palmer et al., 1992; Sataloff et al., 2007; Hannam et al., 2008). All of these muscles arise inferiorly to the hyoid bone and insert to the sternum, the thyroid cartilage, and the scapula. The infrahyoid muscles work in conjunction with the suprahyoid muscles to stabilize the hyoid bone. While the suprahyoid muscles pull the lower jaw beneath and the hyoid bone backward to provide mouth opening, the infrahyoid muscles hold the level of the hyoid bone constant, and have function to control or limit the upward movement of the hyoid bone (Palmer et al., 1992; Naeije and Hofman, 2003; Sataloff et al., 2007; Hannam et al., 2008). Therefore, the infrahyoid muscles together with suprahyoid muscles have the function to control mandibular positions, jaw motions, the hyoid movements, and the tongue movement in the function of speech and swallowing (Palmer et al., 1992; Naeije and Hofman, 2003; Sataloff et al., 2007).

Innervation

The TMJ and the region are innervated by the mandibular nerve, a division of the trigeminal nerve. The auriculotemporal and masseteric nerve branches of the mandibular nerve, innervate the muscles of the TMJ, especially the muscles of mastication (masseter, temporal, medial and lateral pterygoid) and the anterior belly of the digastric muscle. The auriculotemporal nerve also innervates the posterior attachment, the lateral joint capsule, and the anterior and medial regions of the TMJ. The deep temporal and the masseteric nerves innervate the medial joint capsule (Neumann, 2010; Okeson, 2013) (Table 14.1).

Kinematics of the temporomandibular joint

Osteokinematics

Osteokinematics pertains to the overall movement of bones with little reference to their related joints (Oatis, 2009; Okeson, 2013). The osteokinematics of the TMJ include depression, elevation, protrusion, retrusion, and lateral excursion (Oatis, 2009; Neumann, 2010). The TMJ is a complex joint system and allows complex three-dimensional motion. The major function of the TMJ is opening and closing of the mouth as well as tearing and grinding of food. Each TMJ can simultaneously act separately, but not completely without influence from the other. All the mandibular movements occur to varying degrees during mastication (Naeije and Hofman, 2003; Mapelli et al., 2009).

Depression and elevation

Mandibular depression, which is mouth opening, is average of 40–50 mm distance in the adult between the incisal edges of the upper and lower front teeth (Neumann, 2010; Okeson, 2013). The functional range of opening is measured by 3 fingers' width or 35 mm for both males and females. Elevation or mouth closing of the mouth is the reversal of the movements of opening. The mandible rotates upward and retrudes (Koolstra et al., 2001; Slavicek, 2010).

Protrusion and retrusion

Protrusion is an anterior translation of the mandible in the horizontal plane (Kuroda et al., 2009). It is an important component of the mouth's opening maximally. Normal protrusion ranges from 6 to 9 mm (Neumann, 2010; Okeson, 2013). Ideally, the functional mandibular protrusion is that the mandibular central incisors move should past the maxillary central incisors by 1–2 mm. Retrusion is a posterior translation of the mandible in the horizontal plane, and is approximately 3 mm (Koolstra et al., 2001; Slavicek, 2010).

Lateral excursion

Lateral excursion is primarily a lateral translation of the mandible in the horizontal plane. The direction of lateral excursion can be described as either contralateral or ipsilateral to the side of the primary muscle action. The lateral excursion is one-fourth of the opening ranges; 10 mm of lateral excursion for a 40-mm opening (Alomar et al., 2007; Neumann, 2010; Okeson, 2013). An average of 11 mm of maximal lateral excursion to each side is considered normal in the adult (Koolstra et al., 2001; Slavicek, 2010).

Arthrokinematics

Arthrokinematics describe the active and passive accessory movements that occur between two joint surfaces (Oatis, 2009; Okeson, 2013). These components of the arthrokinematic motions are essential to the osteokinematic movements of the mandible. The arthrokinematics of the TMJ involve both rotation and translation (Mapelli et al., 2009; Oatis, 2009; Neumann, 2010; Okeson, 2013).

In the TMJ, rotating movement occurs mainly between the disc and the condyle in the lower joint compartment. The rotational movement of the mandible can occur in all three planes, which are transverse, frontal and sagittal planes. In each plane, it occurs around an axis (Okeson, 2013). In the masticatory system, rotation occurs when the mouth opens and closes around a fixed axis with no positional change of condyles. The rotation or hinge movement of the mandible around a transverse axis passing through the centers of the mandibular condyles is probably the only pure rotational movement. In all other movements, rotation around the axis is accompanied by a translation of the axis (Okeson, 2013).

Translational movements can be defined as a movement in which every point of the moving object simultaneously has the same direction and velocity (Okeson, 2013). In the masticatory system, translational anteroposterior and mediolateral translatory movements occur predominantly in the superior joint space between the articular eminence and disc of the temporomandibular articulation when the mandible moves. The disc moves in the direction of the translating condyle (Tanaka et al., 2003; Tanaka and van Eijden, 2003; Tanaka and Koolstra, 2008). Mapelli et al. (2009), assessed the relative contribution of rotation and translation of the temporomandibular condyle-disc assembly during opening and closing movements in healthy subjects, and found mandibular translation was present during the whole motion, even though it was always smaller than the rotation, and decreased during the mouth opening. During movements of the mandible, both rotation and translation movements occur simultaneously. Mandibular rotation was always larger than the translation. In normal subjects, mouth opening and closing as modeled at the interincisor point was determined more by mandibular rotation than by translation, but on no occasion a pure rotation was found.

Depression and elevation

The action of the mouth opening and closing is a complex series of controlled rotations and translations. The arthrokinematics of the mouth opening involves depression of the mandible (Tanaka and Koolstra, 2008; Ingawale and Goswami, 2009; Neumann, 2010). Rotation and translation occur simultaneously during the depression phase. The condylar head moves anteriorly, but the body moves posteriorly, called posterior rotation of the condyle, is the primary movement at the early phase of mouth opening (Sataloff et al., 2007; Neumann, 2010) (Fig. 14.2A).

The rotation movement occurs in the lower joint compartment, which stretches the oblique portion of the lateral ligaments. In the late phase of mouth opening, anterior translation dominates the opening in the superior joint cavity between the articular eminence and the superior border of the disc (Sataloff et al., 2007; Mapelli et al., 2009; Neumann, 2010). The disc and the condylar head translate anteriorly and inferiorly together as a unit against the slope of the articular eminence (Fig. 14.2B).

Full opening of the mouth maximally stretches and pulls the disc anteriorly (Tanaka and van Eijden, 2003; Manfredini, 2009). At this point, the forward translation is limited by tension in the superior retrodiscal lamina. While the intermediate region of the disc translates

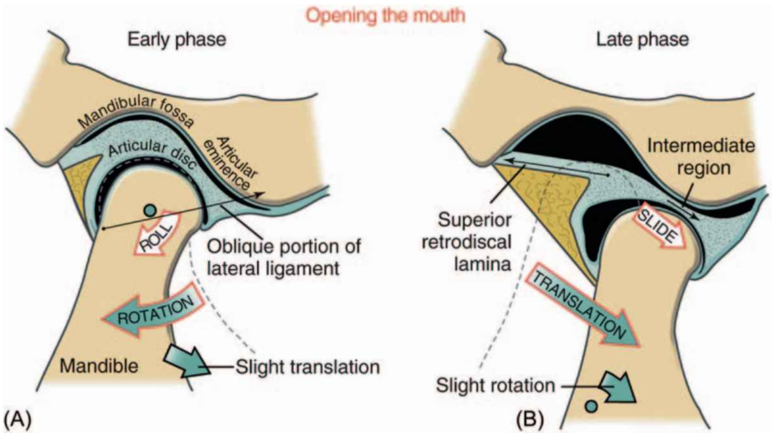

FIGURE 14.2 Arthrokinematics of opening the mouth, illustrated for the right TMJ. (A) Posterior rotation of the condyle; (B) Anterior and inferior translation of the disk and the condylar head.

forward, it remains between the superior aspect of the condyle and the articular eminence. At the end of mandibular opening, both the disc and condyle translated anterior in relationship to the temporal bone as the disc rotated posteriorly on the condyle (Tanaka and van Eijden, 2003). This placement of the disc maximizes the joint congruency and reduces the intra-articular stress (Manfredini, 2009).

The arthrokinematics during the closing of the mouth, the elevation of the mandible occurs in the reverse order of that described for opening. Tension in the superior retrodiscal lamina starts to retract the disc. The condylar head translates posteriorly along with the disc, and then the condyle rotates anteriorly (Mapelli et al., 2009). At the end of the range of closing the mouth, the disc rotates slightly anterior as a result of the contraction of the superior head of the lateral pterygoid (Tanaka and van Eijden, 2003; Manfredini, 2009; Neumann, 2010). The mouth closing is terminated when contact is made between the teeth (Fig. 14.3).

Protrusion and retrusion

The mandibular condyles and the articular disc translate together anteriorly during the protrusion or posteriorly during the retrusion (Ingawale and Goswami, 2009; Neumann, 2010). Therefore, the movement occurs primarily in the upper compartment of the TMJ, and it is symmetrical (Alomar et al., 2007). The posterior portion of the joint capsule limits the protrusion, while the retrusion is limited by anterior ligaments and muscle fibers, and the mass of the retrodiscal pad of the disc (Manfredini, 2009). Because the retrodiscal tissue is very vascular and well innervated, compression or irritation of the retrodiscal pad by excessive or sustained retrusion may produce TMJ pain. During the protrusion of the mandible, the intermediate zone of the articular disc is compressed between the condylar process and the articular eminence (Tanaka and van Eijden, 2003).

Lateral excursion

A lateral excursion of the mandible involves the rotation of the ipsilateral condyle, and the horizontal translation of the contralateral condyle (Ingawale and Goswami, 2009; Neumann, 2010). The contralateral condyle and its disc move anteriorly, inferiorly, and medially along the articular eminence, causing deviation of the mandible toward to the opposite side as the ipsilateral condyle rotates laterally around a vertical axis and moves slightly laterally (Ingawale and Goswami, 2009; Kuroda et al., 2009; Okeson, 2013). On the ipsilateral side, a very limited movement consists, and the articular disc is stabilized between the mandible and the temporal bone.

Mastication

Mastication is the action of chewing foods. It represents the initial stage of digestion, when the food is crashed into small particle sizes prior to swallowing. Many structures, tissues and functional units are involved. Lips, teeth, tongue and soft palate involve actively during the action of chewing foods (Palmer et al., 1992; Slavicek, 2010). The ability of the masticatory organ to crush and preprocess food can be related to vital functions and general state of health. The reduced ability to chew has a significant impact on an individual's digestion, gastrointestinal disorders and health (Slavicek, 2010).

Mastication involves rhythmic and repetitive separation and closure movement of the mandible. This each opening and closing movement of the mandible gives us a chewing cycle, which lasts average about 0.7 s (Gibbs and Lundeen, 1982; Koolstra et al., 2001; Slavicek, 2010). The mastication or chewing cycle start with the opening phase, followed by the closing (crushing) phase and ended with grinding (power stroke) phase. The act of chewing occurs generally on one side of the mouth at a time and called working side, while the opposite side is known as the balancing

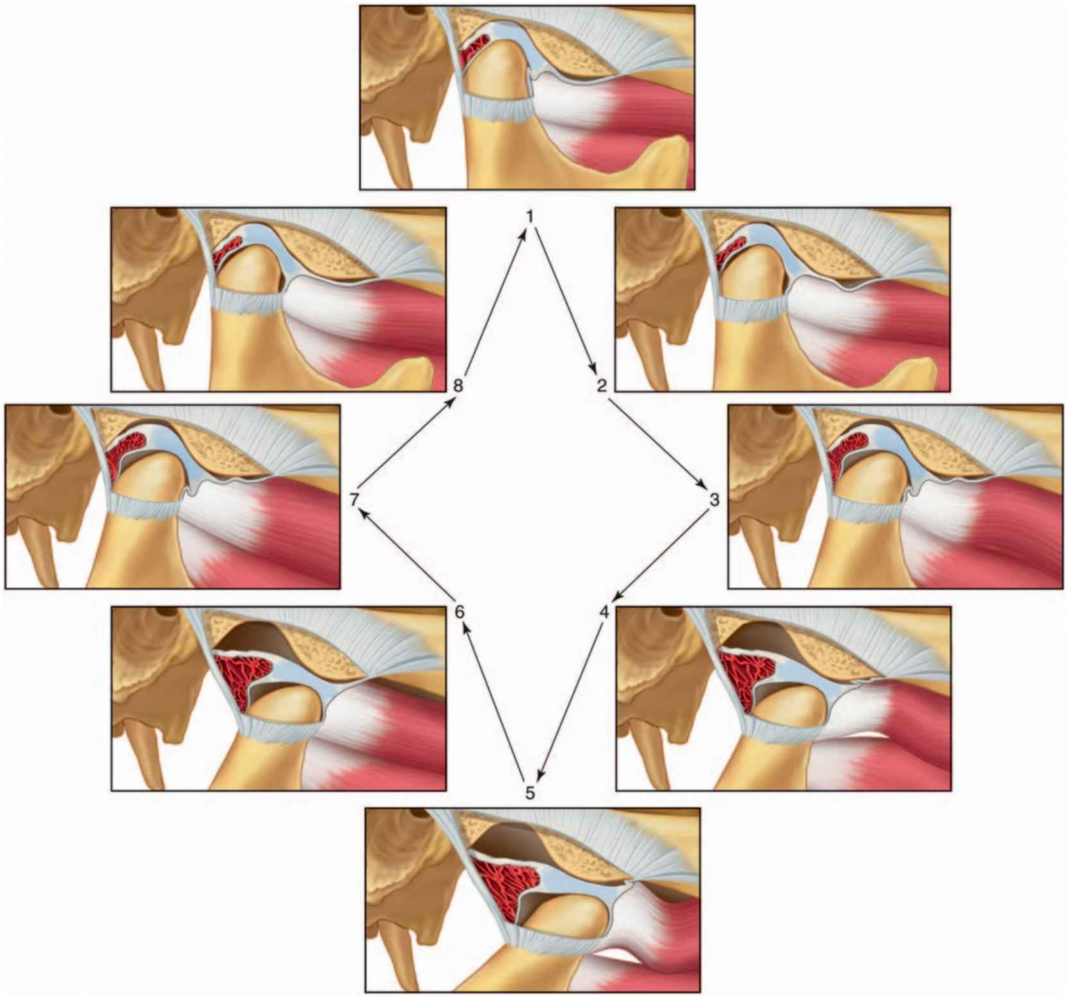

FIGURE 14.3 The opening and closing of the mouth.

side (Koolstra et al., 2001; Naeije and Hofman, 2003; Mapelli et al., 2009; Slavicek, 2010).

Motions of the mandible during the mastication is a three-dimensional, complex motion, which has been described as having the shape of a teardrop or a pear (Neumann, 2010) (Fig. 14.4).

When the motion is traced in the frontal plane during a single chewing stroke, this analogy becomes clear. During the opening phase, the mandible is depressed vertically, where the lower incisor is nearly perpendicular to the dental occlusal plane (Koolstra et al., 2001; Naeije and Hofman, 2003) with inter-incisal gaps reaching 17–20 mm. In the closing phase, the incisor region typically deviates laterally about 5 mm from the midline, and then moves medially as the food bolus engaged (Miyawaki et al., 2001, 2004; Piancino et al., 2008). The mandibular condyles' lateral translation is about 0.4–0.6 mm during the chewing (Miyawaki et al., 2001, 2004). As the mandible continues to close, the food is trapped between the teeth, and the grinding phase, the last phase of the chewing begins. This is the power stroke with forceful contact with the food between the occlusal surfaces of the molar and premolar teeth. During the

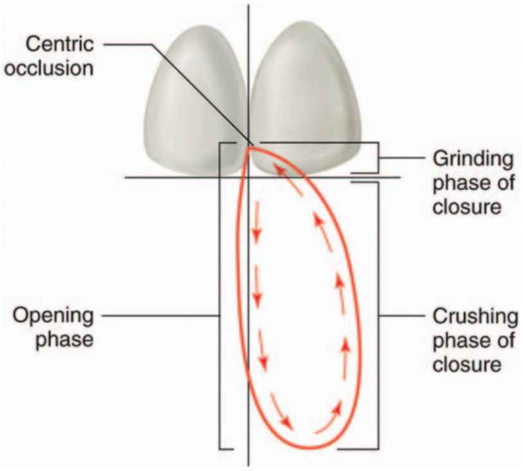

FIGURE 14.4 The Mastication.

grinding, the working side teeth posterior to the canine are moved back toward the midline, permitting shearing and grinding of the bolus of food (Hylander and Crompton, 1980; Nishigawa et al., 1997; Piancino et al., 2009). The mandibular condyle rotates around its ipsilateral condyle as the contralateral condyle returns to its articular fossa (Miyawaki et al., 2001, 2004).

TMJ movements during the chewing are part of a kinetic chain, synchronizing with rhythmical motions of the hyoid, tongue and soft-palate (Hiiemae and Palmer, 2003; Matsuo et al., 2005; Hannam et al., 2008). Studies in two-dimensions suggest that hyoid moves about 3.4 mm upwards and 1.6 mm forwards relative to the occlusal plane, and returns to its initial position near the end of jaw-opening (Hiiemae and Palmer, 2003; Hannam et al., 2008).

Kinetics of the temporomandibular joint

Muscle activation and stabilization of the TMJ

Mastication is a complex coordinated neuromuscular function involving fast, effective mandibular movements, and continuous modulation of the muscle force (Slavicek, 2010). It requires coordinating activity of several muscles, of face, jaw, tongue to produce the rhythmic opening, closing, protrusion, retrusion, and side-to-side translation that produces the chewing stroke (Palmer et al., 1992; Farella et al., 2008; Piancino et al., 2009). EMG studies provide information about the chewing pattern and the relative amount of muscle forces on both chewing and balancing side (De Felicio et al., 2012, 2013). These are to move the mandible in the masticatory path, maintain appropriate alignment between the disc and the mandibular condyle, stabilize the balancing side of the mandible, and control the food to optimize mastication.

The opening stroke is initiated by the activity of the depressor group muscles, which are the supra and infrahyoid muscles (Hannam et al., 2008; Neumann, 2010). Then, the inferior heads of the lateral pterygoid muscles at both sides begin to contract (Murray et al., 2001) causing anterior translation of the mandible during the opening. When the level of activity in the balancing side lateral pterygoid muscle inferior head exceeds that of the chewing side muscle, the chewing side corpus moves back toward to the midline during the opening (Hylander and Crompton, 1980; Nishigawa et al., 1997; Miyawaki et al., 2004; Farella et al., 2008; Piancino et al., 2009).

The three elevators of the mandible, temporalis, masseter, and medial pterygoid muscles work together to raise and deviate the mandible to produce forceful grinding of food (Farella et al., 2008). The closing stroke is initiated by contraction of superficial masseter and medial pterygoid muscles of balancing side; the mandible deviates contralaterally to the chewing side. Then the closing is followed by contraction of anterior temporalis muscle of the balancing side, and superficial masseter and medial pterygoid muscles of the chewing side. The closing stroke is ended by activation of posterior temporalis muscle of the balancing side (Farella et al., 2008; Neumann, 2010). This causes the chewing side of the mandible eventually moving back toward the midline (Nishigawa et al., 1997; Farella et al., 2008). The mandibular elevators on chewing and balancing sides work together to stabilize the mandible during the closing and grinding phases. The activity of the muscles on the balancing side add additional force to the bite force, stabilizing the mandible to maintain the bite location on the teeth (Hylander and Crompton, 1980; Nishigawa et al., 1997; Miyawaki et al., 2004; Piancino et al., 2009; Slavicek, 2010).

The activity of the superior head of the lateral pterygoid muscle during the chewing cycle is still controversial. The muscle activation of the superior head occurs during the closing and/or the early part of the power stroke (McNamara, 1973; Wood et al., 1986; Wilkinson, 1988; Murray et al., 2001), and helps to control the tension within the disc and the mandible. The inferior head of the lateral pterygoid muscle produces the protrusion of the mandible that companies the mandibular depression during the opening phase of the mastication (Murray et al., 2001; Okeson, 2013).

After the activity of the elevators reaches maximum force, the elevator muscles relax and the jaw depressors begin to develop tension. The entire cycle is repeated until the food is broken down into small sizes prior to swallowing (Slavicek, 2010).

The amount of the force placed on the teeth during mastication varies greatly from individual to individual. The muscle activation during masticatory movements depends also on the size and texture of the food bolus to facilitate efficient crushing of the bolus on the chewing side (Piancino et al., 2008). The bolus among the teeth on the chewing side tends to distract the TMJ on the working side, and narrows the joint space on the balancing side (Miyawaki et al., 2001). The larger the food is to chew, the more compression occurs on the balancing side (Hansdottir and Bakke, 2004; Farella et al., 2008).

According to studies the mandibular function is not limited to the muscles of mastication. The accessory muscles of mastication include the suprahyoid and infrahyoid muscles as well as the muscles of the tongue and face (Palmer et al., 1992; Hiiemae and Palmer, 2003; Sataloff et al., 2007). Without coordination between all muscles of mastication and neural input the chewing function cannot be accomplished (Palmer et al., 1992; Ho, 2001; Koolstra et al., 2001). Moreover, a synergistic relationship between the structures of the neck and the TMJ has been described (Makofsky, 1989; de Wijer et al., 1996; La Touche et al., 2011;

Walczynska-Dragon and Baron, 2011). Neck muscles and head position play a major role in stabilizing the cranium and movements of the mandible (Makofsky, 1989). The cranium and mandible, both have muscular and ligamental attachment to the cervical area, therefore, a dynamic balance exists among all of the head and neck muscles (Walczynska-Dragon and Baron, 2011). It is well known that cervical spine tissues can refer pain to the head and orofacial region (La Touche et al., 2011; Walczynska-Dragon and Baron, 2011). Since cervical and masticatory muscle function reciprocally, there is no movement in the neck that would not be reflected in the jaw musculature (de Wijer et al., 1996). Studies have found a positive relationship between extension of the head, which is forward head posture (FHP), and activity of the masseter muscles (Darling et al., 1984; Goldstein et al., 1984; Lee et al., 1995; Visscher et al., 2000; Fernandez-de-las-Penas et al., 2006; Ohmure et al., 2008; Tuncer et al., 2013a,b), and often suggested a factor in the etiology of Temporomandibular Dysfunction (TMD). FHP is defined with shortening of the posterior cervical extensor muscles and tightening of the anterior cervical muscles (Tuncer et al., 2013a,b). In addition, it is characterized by a dorsal flexion of the head together with the upper cervical spine (C1–C3), and accompanied by a flexion of the lower cervical spine (C4–C7) (Ohmure et al., 2008; Tuncer et al., 2013a,b). When the head is held in a forward, the mandibular condyle is pulled slightly downward during the opening and closing movements (Lee et al., 1995; Ohmure et al., 2008). Studies have showed FHP influences not just static changes in mandibular rest position (Darling et al., 1984; Ohmure et al., 2008) and in masticatory muscle activity (Goldstein et al., 1984; Silveira et al., 2015), but also changes in the mandibular kinematics (Visscher et al., 2000; La Touche et al., 2011).

Mechanical loading in the TMJ

The TMJ is one of the heavily loaded joint in the human body. Its biomechanical balance has a great significance to its function. Since the study of Brehnan et al. (1981), which the condylar loading in the macaque was measured directly, it is generally accepted that mechanical loading in the joint is essential for the growth, development, and maintenance of living tissues. Loading in the TMJ may stimulate remodeling, resulting in increased synthesis of extracellular matrices to ensure the homeostasis of joint form, and functional and occlusal relationships (Brehnan et al., 1981; Stegenga et al., 1989).

Mandibular motions result in static and dynamic loading in the TMJ. During the natural loading of the joint, combinations of compressive, tensile, and shear loading occurs on the articulating surfaces (Tanaka and Koolstra, 2008; Oatis, 2009; Neumann, 2010). Studies have indicated that there is a compression in the TMJ during the closing stroke (Langenbach and Hannam, 1999; Christensen and McKay, 2000; Tamura et al., 2003; Huang et al., 2006). Experimental and model studies have examined the stress distributions in the TMJ during a normal jaw closure. The results have demonstrated that the stress (force/area) in the mandibular condyle is dominantly compressive loads, and in the eminence complex are dominantly tensile loads (Chen et al., 1998; Herring and Liu, 2001).

During unilateral chewing the TMJ reaction forces often vary between the balancing and working sides (Nishigawa et al., 1997; Ingawale and Goswami, 2009). Experiments in macaques (Hylander and Crompton, 1980) and on human adult mandibles (Hansdottir and Bakke, 2004; Farella et al., 2008) confirm that joint reaction forces are higher on the contralateral side. Chewing is strongly dependent on the muscles that are involved in mastication. Forceful contraction of the mandibular elevators on the chewing side produces a lateral deviation and tends to produce a rotation of the mandible on the balancing side toward the chewing side (Miyawaki et al., 2001; Naeije and Hofman, 2003). In other words, during the chewing, the distances tracked by the condylar kinematic centers were found to be shorter on the ipsilateral side than on the contralateral side (Huang et al., 2006). Because of that, the chewing side joint is loaded less during the mastication than balancing side (Naeije and Hofman, 2003), explaining why patients with joint pain occasionally report less pain while chewing on the painful side.

Mechanical loading in the articular disc

The articular disc in the TMJ has an important functional role. It fills the space between the condyle and the temporal bone, and acts as a stress absorber and distributors during the jaw activity. The disc also provides a passive mobile articular surface obliging the translational movement made by condyle (Tanaka et al., 2003; Tanaka and van Eijden, 2003). During the jaw movements while natural loading of the joint, the disc is experienced combinations of compression, tension, and shear types of loading (Tanaka et al., 2003; Tanaka and van Eijden, 2003; Tanaka and Koolstra, 2008).

The disc becomes shorter during compressive loading, stretches during the tensile loading in the loading direction. When the disc experiences shear loading, it moves parallel to an adjacent surface (3,6). Studies have found (Nagahara et al., 1999; Perez del Palomar and Doblare, 2007; Commisso et al., 2014; Li et al., 2014), during the jaw opening, the highest compressive stress occurs in the intermediate zone of the disc, whereas the anterior and posterior bands experience mainly tension stress. During the bruxism (Commisso et al., 2014), the disc intermediate zone mainly experiences compressive stresses at the onset of clenching, while shear stresses have been found higher in the anterior and intermediate zones.

Pathomechanics of the temporomandibular joint

When the kinematics of the TMJ may alter, the pathokinematics lead to dysfunctions in intra-articular or extra-articular structures or both (Ho, 2001; Manfredini, 2009; Oatis, 2009). Temporomandibular disorders (TMDs) are a broad group of clinical problems involving the temporomandibular joint, masticatory muscles or both, muscles of the head and neck, and surrounding bony and soft tissue components (Dworkin et al., 1990; Okeson, 2013). The etiology of TMD is complex and multifactorial (Dworkin et al., 1990; LeResche, 1997; Manfredini et al., 2011). Trauma, disc deformation, occlusal abnormalities, and steepness of the articular eminence, hyperactivity of the mastication muscles, and joint hypermobility or degeneration have all been proposed as risk factors. Many factors are also associated with the causes of TMD, including stress, oral parafunctional habits, bruxism, postural dysfunction like chronic forward head posture, or sensitization of the central nervous system (Manfredini et al., 2005; Sale and Isberg, 2007; Svensson et al., 2008; Fernandez-de-las-Penas et al., 2009; Latremoliere and Woolf, 2009; Vedolin et al., 2009; Giannakopoulos et al., 2010; Fillingim et al., 2011; Harper et al., 2016; Slade et al., 2016). Psychophysiological problems that make changes in chewing muscles can lead to pathological changes in the TMJ (Manfredini et al., 2005; Lavigne et al., 2008; Svensson et al., 2008; Vedolin et al., 2009; Giannakopoulos et al., 2010; Fillingim et al., 2011; Harper et al., 2016). The term bruxism is defined as a repetitive jaw muscle activity characterized by clenching or grinding of the teeth and/or by bracing or thrusting of the mandible (Lavigne et al., 2008). As a result, a mechanical load is applied to the muscles and joints (Manfredini et al., 2005; Lavigne et al., 2008; Svensson et al., 2008). Occlusion has long been regarded as a primary etiologic factor for TMD (Manfredini et al., 2011; Okeson, 2013). However, recent scientific literature has not supported a relationship between the occlusal factors and TMDs (Manfredini, 2009; Manfredini et al., 2017).

Epidemiologic studies show prevalence from 44% to 75% in populations having at least one sign of joint dysfunction, and approximately 33% of persons have at least one symptom (Dworkin et al., 1990; LeResche, 1997; Manfredini et al., 2011). TMD is primarily a condition of young and middle-aged adult (20–40 years old), rather than of children or the elderly, and occurs more often in women as in men (Dworkin et al., 1990; LeResche 1997). Sign and symptoms of TMD may include decreased mandibular range of motion, pain in the muscles of mastication and the TMJ, muscle spasm, joint sounds, joint locking, reduced bite force, functional limitation or deviation of mandibular movements, neck pain, and headache (Dworkin and LeResche, 1992; Liu and Steinkeler, 2013; Graff-Radford and Bassiur, 2014; Kraus, 2014; Schiffman et al., 2014; Fernandez-de-las-Penas and Svensson, 2016). Pain is the most common symptom and the most frequent reason for seeking TMD treatment (Harper et al., 2016). Functional movement like chewing, eating, yawning, or speaking aggravates the pain.

The most accepted and worldwide used diagnostic criteria are the Research Diagnostic Criteria for Temporomandibular Disorders (RDC/TMD) proposed in 1992 (Dworkin and LeResche, 1992). In 2013, an interprofessional consortium revised the criteria to improve reliability, validity, sensitivity, and specificity of the examination of the RDC/TMD, resulting in the Diagnostic Criteria/Temporomandibular Disorders (DC/TMD) (Schiffman et al., 2014). In addition, the classification of the American Academy of Orofacial Pain (AAOP) is often used in the clinical settings (de Leew, 2013).

The DC/TMD describes two axes for examination. Axis I cover the physical examination in the muscle and joint areas and divided into three groups; the muscle disorders; the joint disorders related to temporomandibular disc derangements, and the joint disorders related to TMJ arthralgia, arthritis, and arthrosis. Axis II focuses on identifying the psychosocial characteristics that play a foundational or indirect role in the primary complaints (Schiffman et al., 2014).

TMDs are often self-limiting, or fluctuating over time, but a small percentage progress to degenerative changes within the joint and causing loss of function (Manfredini et al., 2011; Liu and Steinkeler, 2013). Musculoskeletal conditions are the most common cause of TMD, accounting for at least 50% of cases, whereas articular disc displacements, involving the condyle–disc relationship are the most common intra-articular cause of TMD (Manfredini, 2009; Liu and Steinkeler, 2013; Fernandez-de-las-Penas and Svensson, 2016).

TMDs related to muscle disorders

Muscle disorders typically include the masticatory muscles and other soft tissues. Most muscle disorders arise from clenching, bruxism, or other parafunctional habits (Svensson et al., 2008; Fernandez-de-las-Penas et al., 2009; Liu and Steinkeler, 2013). It can also be caused by direct trauma to the jaw or indirect trauma from acute or chronic whiplash injury to the neck (Sale and Isberg, 2007), or repetitive microtrauma to the TMJ from parafunctional habits (Manfredini et al., 2005; Lavigne et al., 2008; Svensson et al., 2008; Vedolin et al., 2009). Emotional stress also predisposes to bruxism, which can trigger myofascial pain and changes muscle forces. This condition leads to masticatory musculature strain, spasm, pain, and functional limitation. It seems that increased stress factors, increases the likelihood of having higher muscle tenderness (Mongini et al., 2007; Dommerholt et al., 2015) and higher-pressure pain hypersensitivity (Fernandez-de-las-Penas et al., 2009; Vedolin et al., 2009) in patients with masticatory muscle disorders. The pain symptoms may be only part of the physical manifestations of emotional distress. Stressful life events may cause higher attention focused on the pain and lead to an increase in the pain level. However, some psychological impairment may just be merely due to the presence of the pain (Giannakopoulos et al., 2010; Fillingim et al., 2011; Harper et al., 2016).

Myofascial pain is the most prevalent cause of TMD (Liu and Steinkeler, 2013; Kraus, 2014; Fernandez-de-las-Penas and Svensson, 2016). Its clinical manifestations include headaches, face pain, jaw pain, neck pain, tinnitus, earache, swallowing difficulty, and radiating pain to the neck and head. Centrally mediated myalgia is a process that involves chronic overuse of muscle, as a result of central sensitization (Sale and Isberg, 2007; Fernandez-de-las-Penas et al., 2009; Latremoliere and Woolf, 2009; Harper et al., 2016; Slade et al., 2016), and is often exacerbated by increased sympathetic nervous system activity. Overuse of masticatory muscles can result in reduced or altered of joint motion and jaw functional activities (Mongini et al., 2007; Dommerholt et al., 2015).

Several authors have suggested that posture relates to the status of health, and poor posture can lead to tension-type headache, pain and TMD (Fernandez-de-las-Penas et al., 2006; Tuncer et al., 2013a,b; Graff-Radford and Bassiur, 2014). Headache attributed to TMD is a new Axis I diagnosis classification (DC/TMD) (Schiffman et al., 2012, 2014). Tension-type headache and migraine have been associated with TMD. Longitudinal studies have found that the development of TMD is accompanied by an increase in headache (Anderson et al., 2011; Schiffman et al., 2012) and treatment of masticatory system has been associated with decreased headache (Ekberg and Nilner, 2006).

The TMJ, cervical spine, head position, and alignment of the teeth are integrally related, and dysfunction in one of these regions may lead to a TMD (Darling et al., 1984; Makofsky, 1989; Lee et al., 1995; Visscher et al., 2000; Bogduk, 2014; Silveira et al., 2015). However, the association between the dental occlusion, cervical and head posture in the presence of TMD has been a matter of debate for years (Manfredini et al., 2012, 2017). Silveira et al. (2015) investigated the association between cervical musculoskeletal impairments and TMDs. They found a strong relationship between neck disability and jaw disability. Craniocervical posture was statistically different between patients with myogenous TMD and healthy subjects. Subjects with TMDs presented with impairments of the cervical flexors and extensor muscles. Also, subjects having a greater disability in the jaw were more likely to have greater disability of the neck.

TMDs related to disc derangements

A disc derangement is defined as a displaced disc relative to the condyle and eminence of the temporal bone (Manfredini, 2009; Neumann, 2010; Okeson, 2013). Displacement of the disc affects the functional joint movement, can cause movement limitation and gives problems with functional jaw activities such as chewing, mouth opening, yawning, talking, smiling, singing and brushing teeth (Karacayli et al., 2011).

Many etiologic factors have been suggested to explain disc derangements (Tallents et al., 1996; Tanaka et al., 2001, 2008a,b; Taskaya-Yilmaz et al., 2005; Molinari et al., 2007; Al-Baghdadi et al., 2014; Julsvoll et al., 2016). Direct or indirect trauma to the jaw may cause stretching, tearing, or rupture of the disc, lateral ligament, or capsule. Bruxism has been reported as a potential cause of disc derangements, since compressive overloading may alter the connective tissue of the TMJ (Lavigne et al., 2008). Morphological changes of the lateral pterygoid muscle such as hypertrophy, atrophy, or contracture has been found in patients with anterior disc displacement without reduction (Tallents et al., 1996; Molinari et al., 2007; Al-Baghdadi et al., 2014). From a biomechanical viewpoint, the capsule, the retrodiscal area, medial and lateral ligaments, and lateral pterygoid muscle are important structures in the pathology of the disc-condyle relationship (Taskaya-Yilmaz et al., 2005; Molinari et al., 2007; Manfredini, 2009). The biconcave shape of the disc plays an important role in the translation phase during mouth movements. When the disc has lost its normal shape (Molinari et al., 2007), disc displacement may be triggered during the translation phase.

The disc displacement can be seen into anterior, anteromedial, medial, anterolateral, lateral or posterior of the head of the mandible. In most cases of internal derangement, the disc is displaced anteriorly and medially to the condylar head (Molinari et al., 2007; Julsvoll et al., 2016). With regard to clinical diagnosis and treatment, two predominant stages of disc displacement are distinguished; the disc displacement with reduction (DDwR) and disc displacement without reduction (DDwoR).

Disc displacement with reduction (DDwR)

When the articular disc glides forward in an anteromedial position, the posterior band of the disc slips back over the

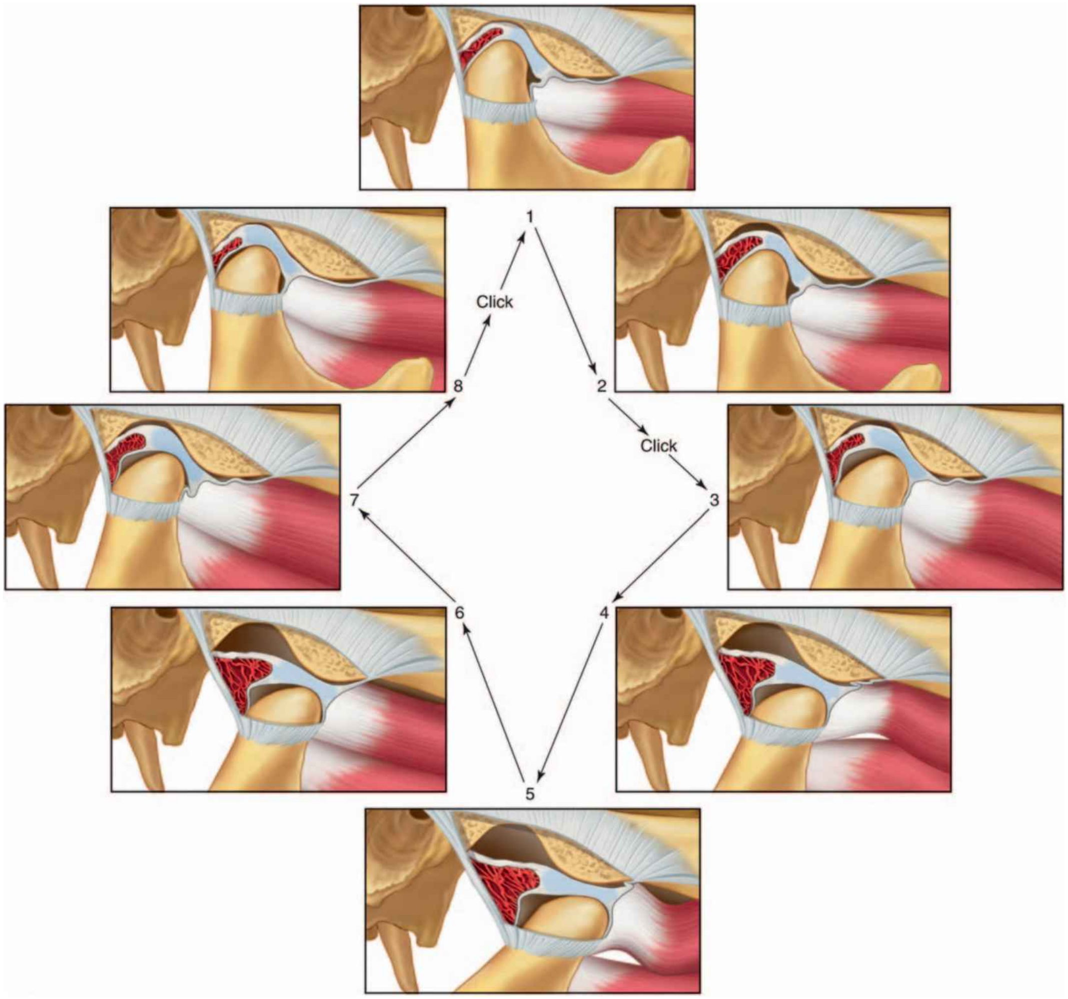

FIGURE 14.5 Disc placement with reduction (DDwR).

condylar head, the mouth opening may occur with a clicking or popping sound. In the open mouth position, the intermediate zone of the disc may be positioned between eminence of the temporal bone and head of condyle at the mouth opening position. Due to relocation of the disc in the TMJ during the opening, it is referred as disc placement with reduction (DDwR) (Molinari et al., 2007; Manfredini, 2009; Okeson, 2013; Schiffman et al., 2014). During closing of the mouth, a second clicking sound may be heard, which called reciprocal click. The condyle slips posteriorly on the anteromedial displaced disc and the posterior band of the disc slips forward off the condyle. This may result in excessive loading of joint structures, causing injury and inflammation, and pain in the preauricular area. Since the retrodiscal tissue, which is richly innervated, has been stretched progressively due to the anterior disc displacement, an increasing deep stretch pain can be felt in the affected (Tanaka et al., 2001; Molinari et al., 2007; Slade et al., 2016). It has been shown that people who had joint sounds, but do not have pain or dysfunction never progress to more severe impairments joint (Tanaka et al., 2008a,b; Okeson, 2013; Slade et al., 2016). A positive history of joint clicking, snapping, palpation of a reciprocal clicks in 1 of 3 trials, and maximum assisted opening of 40 mm or greater are indicative of DDwR (Okeson, 2013; Schiffman et al., 2014) (Fig. 14.5).

Disc displacement without reduction (DDwoR)

The next category of internal derangement, once the disc displacement anteriorly is found a greater degree and the condyle inability to glide anteriorly, may cause decreased jaw movements and limited mouth opening since the disc acts as an obstacle and prevents normal anterior translation of the mandible. It is referred as disc displacement without reduction (DDwoR) or a closed lock (Tallents et al., 1996; Tanaka et al., 2001; Taskaya-Yilmaz et al., 2005; Molinari et al., 2007; Al-Baghdadi et al., 2014; Julsvoll et al., 2016). Due to this reduced glide, one-sided

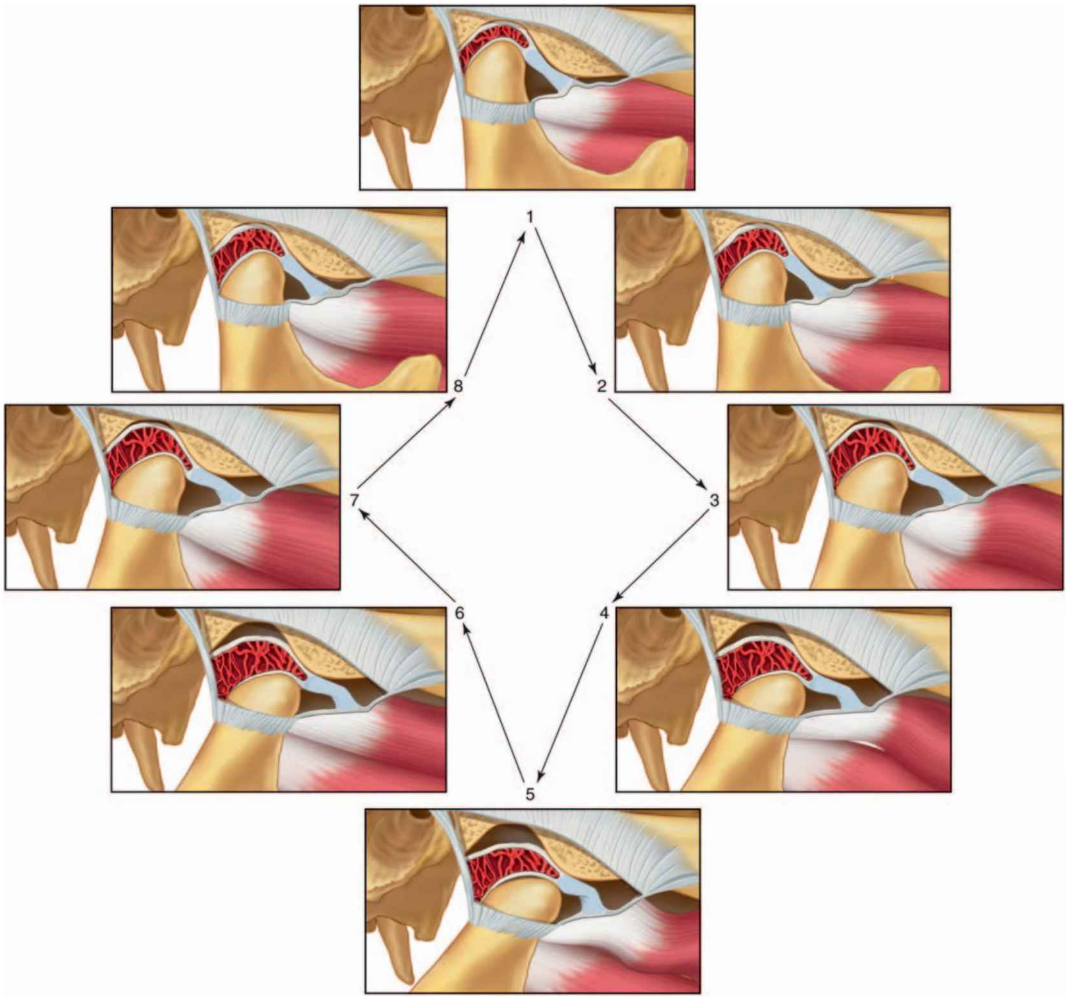

FIGURE 14.6 Disc displacement without reduction (DDwoR).

DDwoR may cause deviation towards the affected, displaced side (Neumann, 2010; Okeson, 2013) (Fig. 14.6).

A history of the jaw catching with a mouth opening of less than 40 mm, decreased jaw movements and deviations, no clicking sounds implicates a DDwoR (Okeson, 2013; Schiffman et al., 2014).

Acute closed lock is associated with limited mandibular opening and severe pain. If locking occurs in the open mouth position, it is probably caused by subluxation of the joint or possibly by posterior disc displacement, which prevents the condyle from returning to its position (Tanaka et al., 2001; Taskaya-Yilmaz et al., 2005; Molinari et al., 2007; Tanaka et al., 2008a,b). At the end of the maximum mouth opening, a click is produced as the condylar head passes the anterior band of the disc, and the condylar head is prevented from returning to its original position. If the patient is able to reduce dislocation it is termed subluxation, and if the dislocation requires an interventional reduction, it is termed luxation (Molinari et al., 2007; Al-Baghdadi et al., 2014; Julsvoll et al., 2016).

Articular disc displacement is associated with TMDs. Studies have shown good reliability for MRI regarding disc displacements. One study has found MRI evidences of disc displacement in 84% of symptomatic patients with TMD versus 33% of asymptomatic patients (Tallents et al., 1996).

TMDs related to TMJ arthralgia, arthritis, and arthrosis

Degenerative joint disease is a frequent finding in the TMJs. TMD's related to degenerative changes of the TMJ are associated with multiple risk factors. Risk factors include age, genetics, trauma, repetitive adverse loading, high-impact and torsional loads, and dysfunctions of joint or muscle, systemic conditions such as generalized osteoarthritis, infection and idiopathic degenerative process, congenital and developmental abnormality (Poveda-Roda et al., 2011; Buckwalter, 2012; Kalladka et al., 2014). It is believed that disc displacement without reduction often progresses to osteoarthritic changes over time (Tallents et al., 1996; Molinari et al., 2007; Tanaka et al., 2008a,b; Al-Baghdadi et al., 2014; Kalladka et al., 2014; Julsvoll et al., 2016). The reasons for progression might be excessive or sustained physical stress to the joint, exceeding the normal adaptive capacity, and leads to degeneration of the articular structure. Degenerative changes may occur when a decreased adaptive capacity of the articulating structures of the joint is present, such as advancing age, systemic illness, and hormonal factors (Buckwalter, 2012; Kalladka et al., 2014). During mandibular movement, patients suffering from arthritis may complain of increasing pain, decreased range of motion, tenderness and severe pain during load bearing.

These pathologies of the joint are classified in the DC/TMD group III of Axis I as arthralgia, osteoarthritis, and osteoarthrosis (Schiffman et al., 2014). Osteoarthritis (OA) is an inflammatory condition associated with a degenerative process (Julsvoll et al., 2016). This inflammatory condition clinically manifests as arthralgia, which is defined as pain and tenderness in the joint capsule and/or the synovial lining of the TMJ. In OA, the patient may report joint pain in the preauricular area, crepitus during jaw movements, and limited range of motion, whereas in osteoarthrosis, degenerative changes are similar with OA, but it is a noninflammatory condition (Poveda-Roda et al., 2011). Degenerative changes may be unilateral or bilateral and has a strong preference for women. It is estimated that approximately 15% of the world's population suffer from osteoarthritis (Tanaka et al., 2001; Taskaya-Yilmaz et al., 2005; Molinari et al., 2007).

Studies on degenerative changes in the TMJ show differential loading in the joint and the most articular disc perforations occur along the lateral aspect of the TMJ (Christensen and McKay, 2000; Julsvoll et al., 2016). This indicates that the lateral aspect of TMJ experience more stress than the medial aspect. In a study, the effects of TMJ arthralgia were evaluated on mandibular mobility, chewing, and bite force in subjects with TMD compared to healthy control subjects (Hansdottir and Bakke, 2004). The pressure pain threshold (PPT), maximum active jaw opening, unilateral bite force was measured. The PPT, maximum jaw opening, and bite force were significantly lower in the subjects with TMD as compared to that in controls. The patients were also found to have longer duration of chewing cycles. The bite force and jaw opening in subjects with TMD were significantly correlated with PPT.

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Chapter 15

Kinesiology of the cervical vertebral column

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Introduction

The cervical vertebrae allow movement of the head while basically carrying the skull. During functional movements flexion-extension, lateral flexion and rotational movements are performed in harmony. While fulfilling these functions, they also protect the spinal cord, that passes through vertebral canal. The movements of the cervical spine show significant differences from thoracic and lumbar regions. The most important difference of cervical vertebrae from thoracic and lumbar region is their unique anatomical characteristics.

Functional anatomy

The cervical spine consists of 7 vertebrae. While the region composed of occiput, C1 and C2 vertebrae, it is usually called as occipito-cervical junction. Thus, C3 to C7 vertebrae are called the sub-axial spine. The C1 vertebra (atlas) is shaped as a rounded ring (Fig. 15.1), and unlike other vertebrae, it has no vertebral corpus anteriorly. There are a number of bone structures called "lateral masses" on either side of this ring-shaped bone. The cranial surface of this mass, which serves as a bone support, has two joint surfaces on the right and left in concave form. These articular surfaces articulate with convex articular surfaces under the skull. Due to its anatomical structure, these joints allow rotational movements. In the caudal region of the lateral masses, there are two articular surfaces that articulate with C2 vertebra. These articular surfaces are shaped mainly for providing rotation, however their anatomical structure also allow minimal flexion and extension. Other joint surfaces at the anterior ring of the atlas and on the surface facing the spinal canal, articulates with the odontoid process of C2 vertebra.

The C2 vertebra has a large body at the front (Fig. 15.2). The cranial extension of this torso is called as

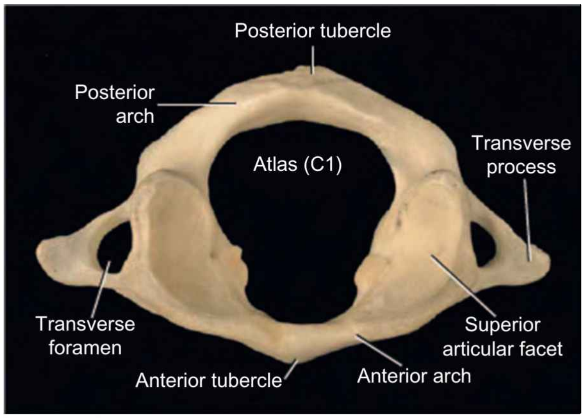

FIGURE 15.1 Superior view of atlas.

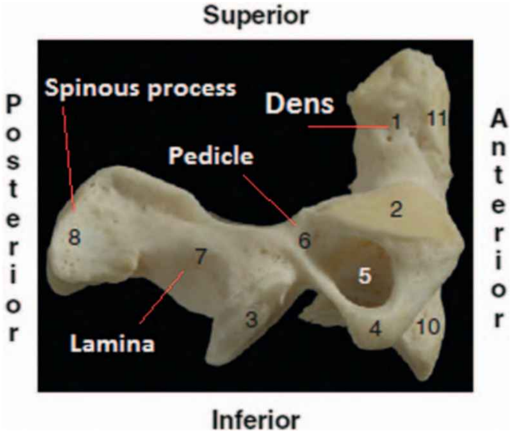

FIGURE 15.2 Lateral view of axis. Inferior surface of axis is similar to subaxial spine.

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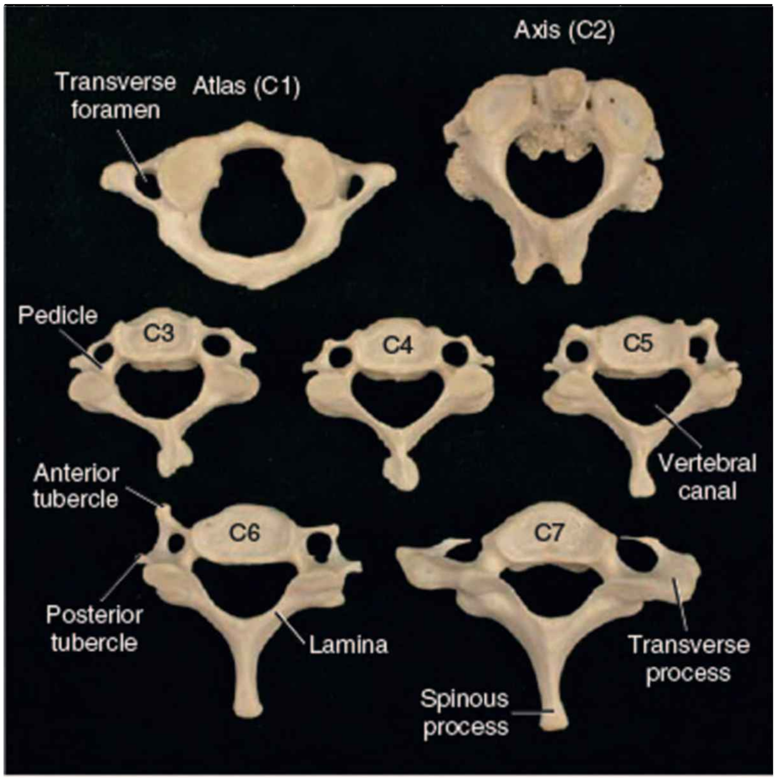

FIGURE 15.3 Articulation of subaxial spine. Lateral deviation of motion segment is restricted by facet joint and uncovertebral joints.

odontoid process, which is articulated with the C1 vertebral arch. The odontoid process is encircled by the transverse ligament extending from the lateral masses of C1 vertebra posteriorly while articulating with the anterior arch of C1. Thus, articulation between C1 and C2 the vertebrae allows for rotational movements around odontoid process. There are two articulating surfaces located on the transverse plane at the sides of the upper surface of C2. Superior articular surfaces articulate with lateral masses of C1. Since the surfaces of these joints are perpendicular to the body, the movement is in the axial plane. There are two foramina on anterolateral corners of C2, where the vertebral arteries pass. The lower surface of the C2 vertebra is similar to other cervical vertebrae.

The vertebrae between C3 and C7 are called sub-axial vertebrae which are anatomically and functionally similar to each other (Fig. 15.3). They have bifid (two headed) spinous processes posteriorly. The spinous process of the C7 vertebra is more prominent than the others, and is called 'vertebrae prominence'. The bone surfaces on the back of the vertebrae are called lamina and form the posterior wall of the spinal canal. The lateral edges of the laminae have superior and inferior articular processes oriented in the frontal plane. The articulation between the inferior articular process of a superior vertebrae and the superior articular process of an inferior vertebra is called as facet joint. Facet joints of the subaxial vertebrae are oriented parallel to the frontal plane and diagonal to the sagittal plane. For this reason, subaxial cervical facet joints allow motions in both sagittal and frontal plane. The superior articular surfaces of the facet joints turn towards the posterior-lateral side caudally (Pal et al., 2001). For this reason, the flexion and extension movements increase in the lower cervical region.

The thickening of the bones in the front and outer parts of the facet joints is called lateral mass. Vertebral foramens are found in the anterior parts of the lateral masses. The anterior parts of the subaxial vertebrae are called corpus. The upper surfaces of the corpus are concave, while the lower surfaces are convex. There are uncinate processes on both sides of the corpus. Articulation between the uncinate processes of two corpii called uncovertebral joint of Luschka. Uncovertebral joints constrain lateral flexion of subaxial vertebrae and mainly allow flexion and extension.

Intervertebral discs are located between the corpus of C2 and T1 vertebrae. The circumference of the intervertebral discs is wrapped with a thick collagen sheath. This sheath is made up of type 1 collagen fibers that extend inward and perpendicular to each other. It is highly resistant to distractive forces due to the arrangement of collagenous fibers. However, ruptures can occur under rotational forces. The center of the disc contains nucleus pulposus. It is a jelly like tissue mainly composed of type

2 collagen and hydrophilic proteoaminoglycans synthesized by disc cells. It is highly resistant to compressive forces and has hydrostatic load bearing properties.

The anterior atlanto-occipital ligament is located between the skull and the C1 vertebrae ventrally. This ligament, extends caudally along entire length of vertebral column as anterior longitudinal ligament. It limits extension of the vertebral column by resisting tensional forces. Posterior ligaments have a more complex structure. A ligamentous structure between the occiput and the posterior arch of the C1 vertebra called posterior atlanto-occipital membrane The fibrotic bands starting from the spinous processes of the C2 vertebrae become thicker caudally and named as ligamentum nuchae. Ligamentum nuchae restricts excessive flexion of the neck. Between the laminae posteriorly, the only elastic ligament of the spine, ligamentum flavum is only the ligament of the spine which is composed of elastic fibrils and also called as yellow ligament. Its elastic structure partially restricts flexion and rotational movements. Additionally, joint capsules cover the surfaces of the facet joints also contribute to the restriction of flexion.

The cervical region muscles are quite numerous and complex. Although many of them extend straight forward, when contracted they may move the skull in all directions because they have different angular orientation to each other. Muscle origins and insertions are described in the kinetic features section.

Kinesiology of the normal cervical vertebral column

Kinematics of cervical vertebral column

When the kinematic characteristics of the spinal column are considered, translational and rotational movements between the vertebrae are understood. The joints between two vertebrae and all the components in between biomechanically form the motional segment. These joints and all the components in between are required to measure the kinematic properties of the motion segment. It is difficult to determine a normal value because such value would be influenced by many factors such as the position of the head, posture in vertical and/or horizontal positions, muscle strength and stiffness of soft structures such as ligaments, muscles and connective tissues. Experimental models were developed based on mathematical measurements of segmental movements on a fixed center of rotation mimicking spinal movements (Vasavada et al., 1998). However, the extent to which kinematic values obtained from the models overlap with the actual data is still controversial.

The occipito-cervical junction comprises two motion segments. One is the atlanto-occipital joint and the other is the atlanto-axial joint. Despite the presence of two motion segments, they act as a single unit providing half of the rotational neck movements. It acts as a hinge between the skull and the cervical vertebrae, which translates the coronal plane movement into an axial plane movement. Joints of occipito-cervical junction and upper cervical spine are oriented in horizontal plane. For this reason, rotation of the head occurs as a main motion of occipito-cervical junction. The main structures that restrict motion and provide stability in this complex are the ligaments. The posterior atlanto-occipital ligament is located between the posterior arch of atlas and the posterior edge of foramen magnum and is responsible to restrict the forward bending of the head (Fig. 15.4). Tectorial membrane, which is an extension of anterior longitudinal membrane, extends from the body of C2 to the posterior side of the anterior arch of C1 and from there to the anterior edge of the foramen magnum. It is stretched during extension of the head and thus restricts extension. It also restricts the flexion slightly as it prevents the skull from translating posteriorly during flexion (Fig. 15.5). The transverse ligament is located at the interior of C1 arch and anterior to the spinal canal and extends from one side to the other (Fig. 15.6). The ligament has a fibro-cartilaginous tissue on the side facing the odontoid which actually articulates with it. This joint allows right and left rotation of the head. Fixation of this joint causes severe limitations in the rotational movement of the head. Upper part of this hinge-like structure is atlanto-occipital joint which has a movement that can be described as in means of both flexion-extension and antero-posterior slide or shift. These varying movements are the result of articular surfaces. Concave ear-like articular surfaces on atlas forms a perfect match for occipital condyles. Relatively long antero-posterior axis of these articular surfaces enables slide or shifting movements which then can be converted into flexion and extension. Thus, any disruption between these articular surfaces may

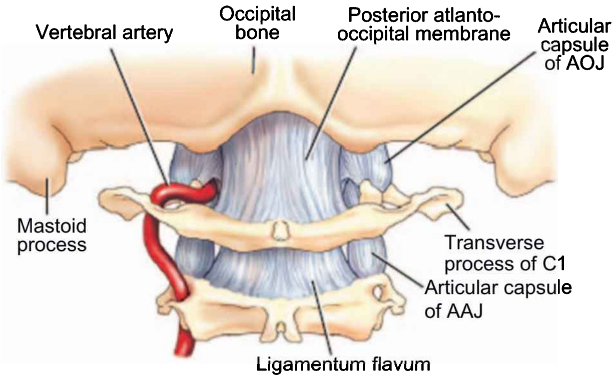

FIGURE 15.4 Posterior atlanto-occipital membrane.

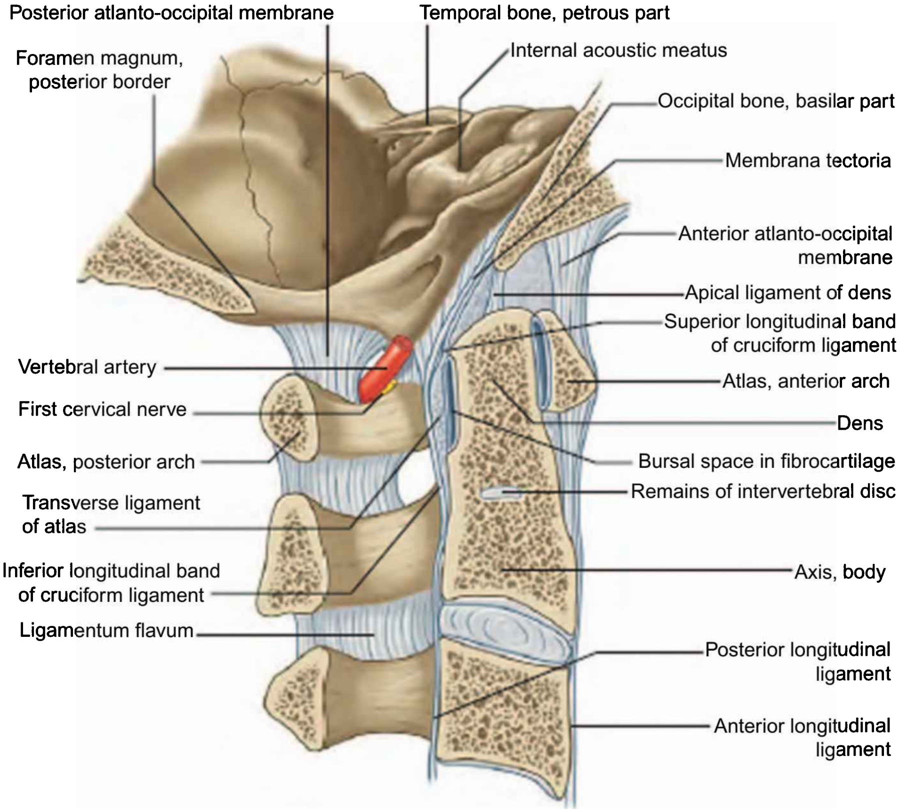
Posterior atlanto-occipital membrane
Temporal bone, petrous part
Foramen magnum, posterior border
Internal acoustic meatus
Occipital bone, basilar part
Membrana tectoria
Anterior atlanto-occipital membrane
Apical ligament of dens
Superior longitudinal band of cruciform ligament
Vertebral artery
Atlas, anterior arch
First cervical nerve
Dens
Atlas, posterior arch
Bursal space in fibrocartilage
Remains of intervertebral disc
Transverse ligament of atlas
Inferior longitudinal band of cruciform ligament
Axis, body
Ligamentum flavum
Posterior longitudinal ligament
Anterior longitudinal ligament

FIGURE 15.5 Function of tectorial membrane at sagittal plane during flexion and extension.

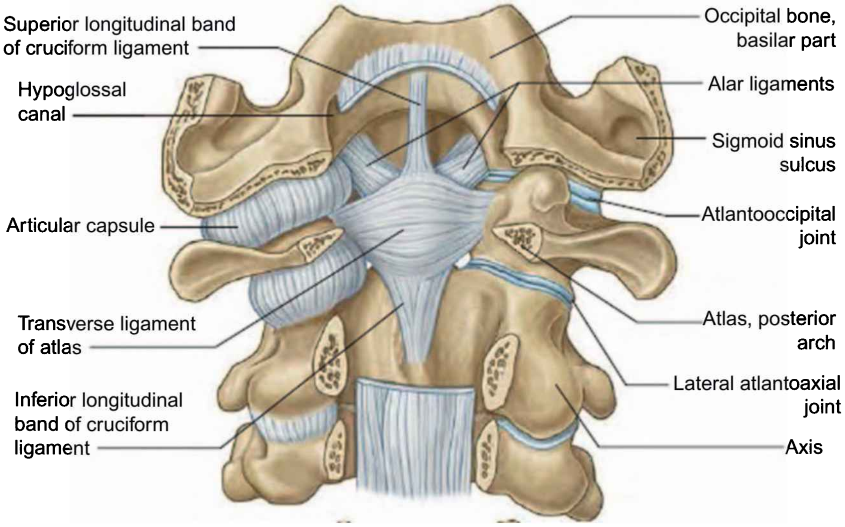
Superior longitudinal band of cruciform ligament
Occipital bone, basilar part
Hypoglossal canal
Alar ligaments
Sigmoid sinus sulcus
Articular capsule
Atlantooccipital joint
Transverse ligament of atlas
Atlas, posterior arch
Lateral atlantoaxial joint
Inferior longitudinal band of cruciform ligament
Axis

FIGURE 15.6 Transverse ligament and its branches.

limit slide/shifting motion and result in reduced flexion-extension movements.

Atlanto-axial joint, responsible for almost 50% of neck rotation movement as described before, has unique properties in terms of kinesiology. This uniqueness appears to come from having 6 degrees of freedom. These movements are defined as axial rotation (45 degrees), antero-posterior and medio-lateral translation (around 2–3 mm), flexion-extension (5 degrees), lateral flexion (2 – 3 degrees) and vertical translation. Before explaining such complex motions, studies also indicated that vertical translation occurs during rotational movements where in neutral position the distance between C1 and C2 is the greatest and in full rotation it is the lowest. This dual

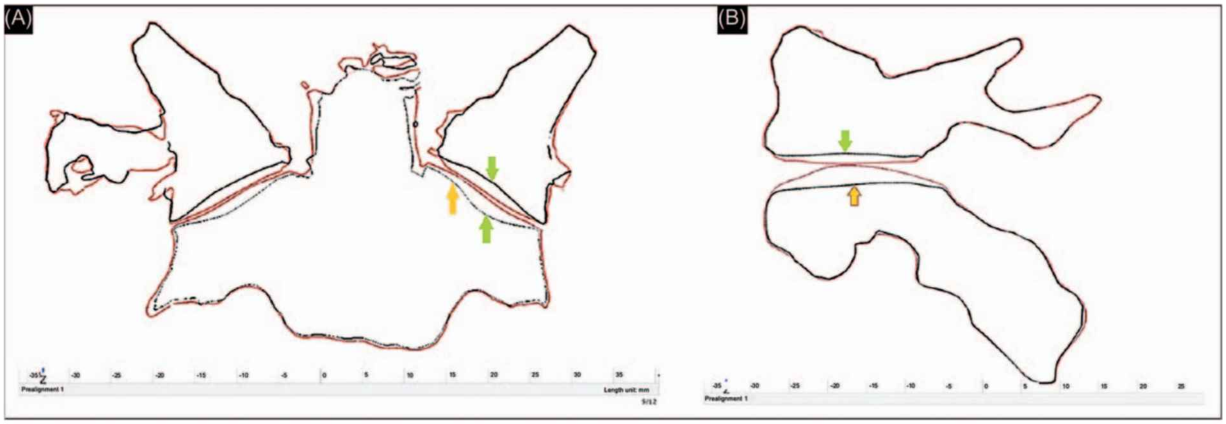

FIGURE 15.7 Rocking motion of subaxial cervical vertebrae. Coronal (A) and sagittal (B) two-dimensional sections passing through the C1-C2 joint is shown. Black line demonstrates the cortical edge of bone and red line marks the cartilage.

motion is described as coupling. Although it was identified that motions other than rotation is also accompanied by aforementioned vertical translation, some of the relevant studies were not be able to fully describe coupling phenomenon occurred during these movements. The reason for this lack of explanation is that the spine tends not to act similar when other segments (thoracic spine and lumbar spine) considered. However, it was shown that atlanto-axial joint has quite interesting bones and articular cartilage surfaces thus coupling phenomenon may be related to the joint architectural design. "But how interesting bones and articular surfaces does atlanto-axial joint have?", answer of this question can be seen in Fig. 15.7 (Prasad et al., 2017).

As in the literature, bony surface of atlas appears to show concavity in frontal and sagittal planes however; in frontal plane it is medially convex and laterally concave. The interesting relation between these surfaces is that articular cartilage on atlas and axis reforms concave on concave-convex joint surfaces into new one: convex on convex. Thus such convex on convex joint surfaces creates a joint which is able to move through all 6 degrees of freedom. Additionally, it was proved that vertical motions during rotations are required to allow fibers of alar ligament to let the motion continue without getting taut. Such vertical motions create the shortest paths between attachments of fibers of alar ligament, thus allow rotation to reach higher degrees free motion. If we think about only motions, flat joint surfaces will be enough to create rotational movement between C1 and C2. Though this movement counts as a simple rotation, we need to sacrifice other coupled movements such as: rotation in lateral flexion, in order to have it with flat joint surface alignment. Also this "simple rotation" requires more "movement area" between joints to reach the same range of motion of normal rotation. In studies, it was shown that increased "movement area" will narrow canalis vertebralis and disrupt medulla spinalis. Coronally inclined joint surfaces enable this segment to compensate the necessary larger area by shifting and creating additional rotation window, in addition to expanding the area for canalis vertebralis. On the other hand, if the inclination of joints in the frontal plane is excessive, movement trail of joint surfaces—in this case a shape of a cone without its sharp end, a frustum- will not be similar, thus leading to unstable segments (Salunke, 2018).

Kinematic measurements of the cervical spine were initiated by direct flexion and extension radiography (Prasad et al., 2017). Some studies have simplified neck movements to define the range of motion between the head and the 7th vertebra (Konig et al., 2005; Salunke, 2018). However, due to individual differences in subjects in static radiographic measurements, inter-observer error rates are between 20% and 60% (Dunsker et al., 1978). For this reason, it is not possible to determine the abnormal movements and it is not possible to determine the end point of the movements. Nevertheless, no study data can exactly be adapted to everyday life. Kinematic studies have been performed with bi-planar cine-radiographic methods during continuous flexion and extension movements (Trott et al., 1996). However, the global movement of the whole cervical spine can be evaluated rather than the movement of each segment due to the continuing movement in these studies. In these studies, cine-radiographic data were analyzed in combination with 3-D CT images (Amiri et al., 2003). Thus, the bone structures contributing to the motion were evaluated in 3D, and some reasonable inter-observer rates were obtained. The most important advantage of dynamic studies and 3D modeling is that they are not greatly affected by the head and body position. The data obtained, thus, can be adapted into clinical scenarios.

Intervertebral discs and zygapophyseal protrusions on the sides allow the cervical vertebra motional segment to

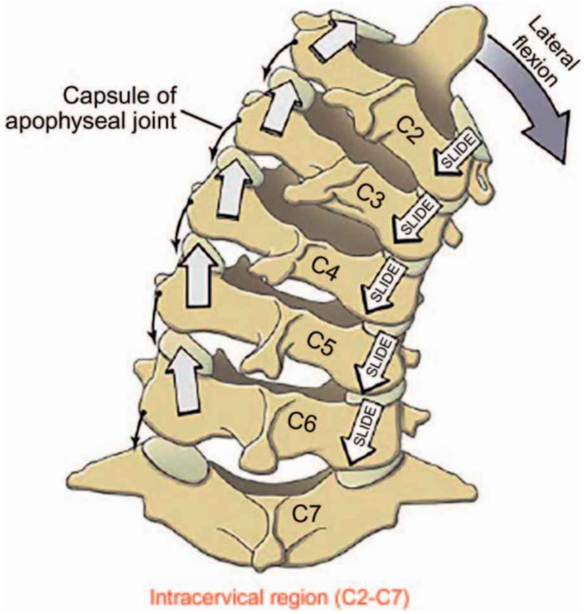

FIGURE 15.8 Origo and insertio of splenius capitis muscle.

move as a ball and socket type of joint, meanwhile, they also cause serious limitations in some movements. The axis of motion which is formed by the disc space and the Luschka joints is close to the horizontal plane. This joint complex basically allows two motions; the first one which actually is a real ball and socket joint articulation is known as rocking motion (Fig. 15.8). This motion can be described as the frontal and sagittal plane motion of the convex end-plate of the upper vertebra on the concave end-plate of the lower vertebra. During this movement while the zygapophyseal protrusions on the sides prevent excessive movement, they also cause the two vertebral bodies to roll over each other which results in some horizontal movement during this frontal and sagittal plane movements. The second motion formed by the intervertebral disc and the zygapophyseal joint complex is the translational motion. Particularly due to the increase in the intra-discal pressure during lateral bending and the overlap of the zygapophyseal joints on the tilted side, the body of the upper cervical vertebra translates laterally on the body of the lower vertebra. However, this movement is rather small and has little effect on daily life. Cervical spine allows the head to move in sagittal, frontal and horizontal directions. Compression of the intervertebral discs may lead to very small amount of axial shortening. If axial loads exceed the physiologic strength of the cervical vertebrae, traumatic injuries may occur.

Normal range of neck movements have been tried to be defined in many studies. According to the results obtained from these studies, the range of neck movement in women is more than men. Range of neck motion is increased with rotation. Besides, range of rotation is decreased with flexion while increases with extension of the neck. Flexion, extension, lateral deviation, and rotational movement ranges decrease with advancing age (Dvorak et al., 1988; Hino et al., 1999).

In a study on localization of neck movements, in healthy women cervical and thoracic movements were measured under voluntary flexion and extension by using two-dimensional optoelectronic system during sitting position. It has been determined that 30% of all head excursion movements are from the cervico-thoracic component (C7 to T4) (Anderst et al., 2014). The remaining sagittal plane movements are provided by the upper levels. In their study of 3D modeling by bi-planar fluoroscopy, Lin et al., separately measured the rotational and lateral bending movements of subaxial motional segments in asymptomatic individuals (Tsang et al., 2013). According to this, the segment with the greatest motion range during rotation is found as C4–5 (4.6 degrees), while the segment with the greatest motion when tilted to the side is measured as C3–4 (6.4 degrees). At the lower levels of subaxial vertebrae, rotational and lateral deviational movements are restricted as opposed to flexion-extension.

Kinetics of cervical vertebral column

The kinetic properties of the neck are quite complex. The most important reason for this is that the muscles that provide the movements are settled in numerous and different vector directions. Some muscles provide direct movement to the neck, while others indirectly contribute to neck movements while moving the neighboring structures. The muscles that move the cervical region can be divided into two groups as functional and static muscle groups. Static muscles maintain the erect posture of the head and upper body. Voluntary head movements are performed by these muscles. Functional muscles are active in eye motions and eating. There is also anatomical classification of muscles in cervical region in terms of consecutive layers. According to this classification cervical region has 6 layers of muscle.

Trapezius muscle, as it is defined as the muscle which controls scapular movements, is formed of 3 lesser muscles (Standring, 2008). As 3 parts of trapezius muscle are referred to upper, middle and lower parts, their function may sometimes differ from each other. It is known that upper and lower trapezius rotates scapula upward with the help of serratus anterior muscle whereas middle part retracts scapula with the help of rhomboid muscles, yet such simple kinematics mostly fail to explain more peculiar features (Wallden, 2014). It was shown that trapezius muscle is not only used for rotating or elevating scapula (Wallden, 2014). After identifying the structure of this muscle, researchers found that it contains type I muscle fibers which contracts much slower than type 2 and also require less neural activation. Lesser need of neural activation of a muscle indicates the muscle contracts according to feed-forward activation. By identifying its innervation by cranial nucleus, it was indicated that trapezius muscle not only has mechanical features but also a sensorial base for postural reactions. Additionally trapezius muscle was found to be one of the key muscles of aerobic capacity, by working in harmony with anteriorly located muscles of aerobic capacity (Wallden, 2014). Studies related to temporomandibular joint dysfunction mention the role of trapezius muscle. Such studies indicated that temporomandibular joint dysfunction may cause both symmetrical and asymmetrical positional changes in cervical spine and shoulder girdle since the tension of the structures that controls temporomandibular joint is controlled by the muscles in the very same location. Such changes include increased fatigue tendency of trapezius muscle related to non-optimal position and presence of trigger points as muscle tries to correct alignment even if its position is non-optimal. Studies also showed that such alterations might occur in reverse order which means chronic spasms or alignment problems may lead to temporomandibular joint dysfunction over time (Ritzel et al., 2007; Dibai Filho et al., 2012). The last but not the least, with attachments of trapezius muscle to nuchal ligament, this muscle also plays an important role during a gait cycle. As it will be discussed in another chapter, gait has quite unique features which help to sustain the cycle with little effort. One of the energy preservation mechanisms of gait is the vertical recoil motions of head. During gait cycle head is lifted upwards thus using the potential energy that is restored in elastic soft tissues -in this case nuchal ligament- and left to free fall from the height like a spring. So recoil and/or tension of nuchal ligament is controlled by trapezius muscle, which indicates its function in gait cycle.

Levator scapula is another muscle that has impact on many regions due to its extensive origins. Considering the layout of levator scapulae it may elevate scapulae however, if the scapula is fixed in place this muscle ipsilaterally flexes and rotates cervical region with the help of its attachments to transverse processes of C1–C4 (Standring, 2008). Importance of levator scapulae comes from its ease to become spasmatic due to its insertion at scapulae, which is a muscle fixated by only the surrounding muscles without any proper joint formation. The most important muscles posteriorly contributing to the head posture are the splenius capitis (Fig. 15.9), semispinalis capitis (Fig. 15.10) and rectus capitis muscles. These muscles extend the head when contracted. At the same time, they also restrict the head to tilt forward in standing posture. The flexion of head is mainly provided by longissimus colli, longissimus capitis and sternocleidomastoid muscles (Fig. 15.11). Scalene muscles also partially contribute to head flexion. These groups of muscles are located deeply except sternocleidomastoid muscle. Origins and insertions of these muscles are at the front of the cervical spine. They flex the head when contracted.

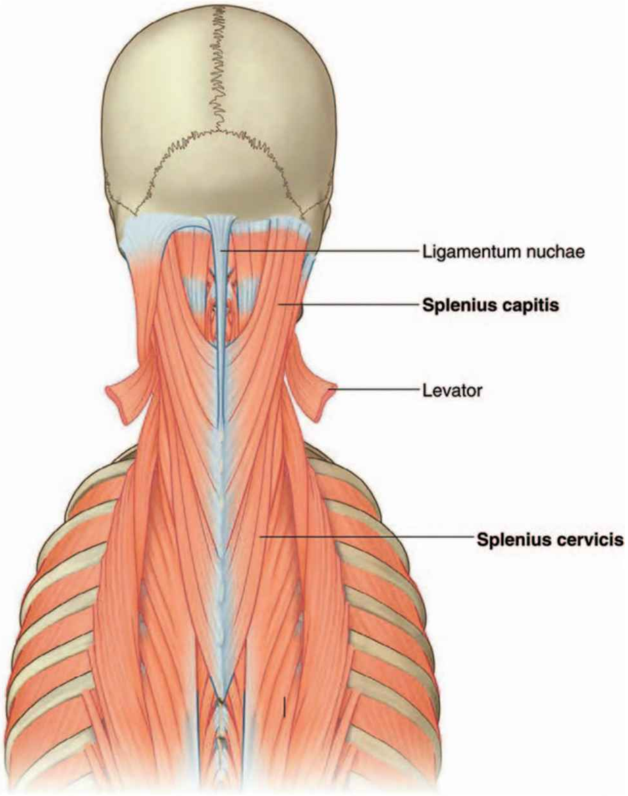

FIGURE 15.9 Posterior aspect of semispinalis muscle.

Erector spina muscles; iliocostalis, longissimus and spinalis (from lateral to medial) are located on the spine orient longitudinally. Although they are able to extend, laterally flex and rotate spine, their main function is to compensate the effect of gravity by keeping spine upright during sitting and standing.

One of the most important muscles during neck movement is the sternocleidomastoid muscle (Fig. 15.12). The sternocleidomastoid muscle originates from two locations: the manubrium of the sternum and the clavicle. It travels obliquely across the side of the neck and inserts at the mastoid process of the temporal bone of the skull. The primary actions of the muscle are rotation of the head to the opposite side and flexion and lateral deviation of the neck to the same side. Lateral bending movement is performed together with scalene muscles.

Instantaneous axis of rotation

During neck movements, each motion segment is considered to be a hinge point that remains in stance phase.

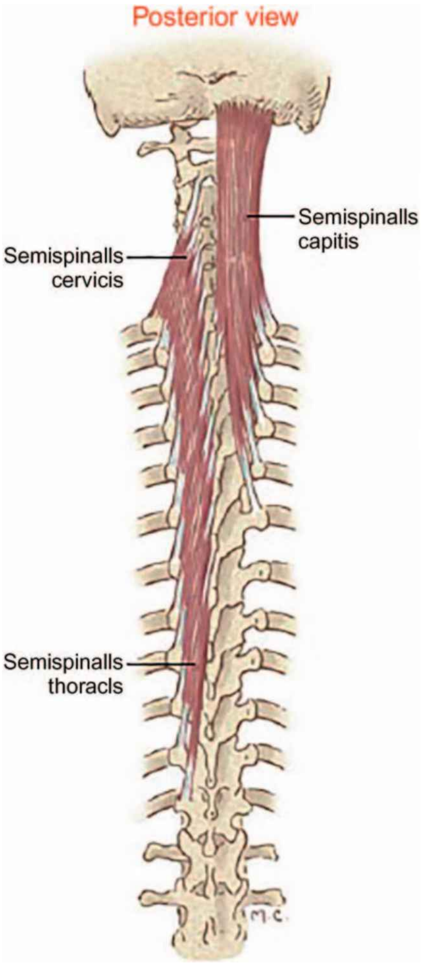

FIGURE 15.10 Anterior view of longus colli and longus capitis muscles.

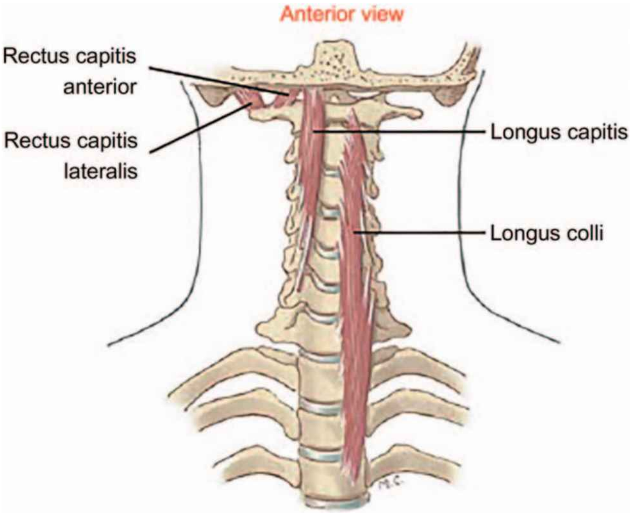

FIGURE 15.11 Lateral aspect of sternocleidomastoid muscle.

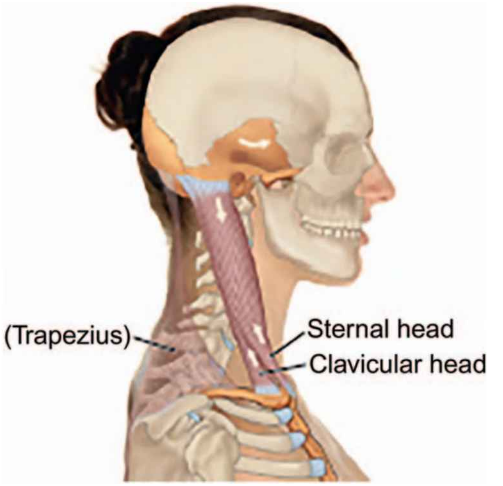

FIGURE 15.12 Bone and articular surface of atlanto-axial joint.

It is believed that this point is fixed relative to the movement plane and that the motion is taking place around this point. This point is named as instantaneous axis of rotation. In the motion segments of the subaxial vertebrae, it is suggested that the instantaneous axis of rotation is located close to the anterior part of the vertebral body (Dvorak et al., 1992).

Cervical vertebral column in pathological conditions

In the previous headlines normal kinesiology of cervical spine was explained but the pathological conditions and alignment problems clinicians encounter in the field were not mentioned. Such conditions may be listed as but not limited to; dislocations, spondylosis, spondylolisthesis, disc herniation, alignment problems caused by trauma and/or muscle strength imbalance and many more. One can only understand such conditions by only understanding the normal kinesiology of cervical spine completely. Thus, under this headline, the context may require readers to recall previously mentioned information in order to deliver the best experience. However sometimes context will help the reader to remember the normal kinesiology by quoting parts in previous headlines.

The joint formed by a unique couple of vertebrae "atlanto-axial joint" has relatively odd bones and articular cartilage surfaces. If the alignment or shape of these surfaces shifts from normal (by factors like abnormal loading or trauma) it may cause a condition called atlanto-axial joint dislocation (AAD). Anatomically most of the joints tend to dislocate into a certain direction where its joint capsule or the supportive tissues become weak but in atlanto-axial joint the dislocation might be multiplanar due to its *unique* joint surfaces. To manage AAD surgeons use the drilling technique on lateral joint surfaces

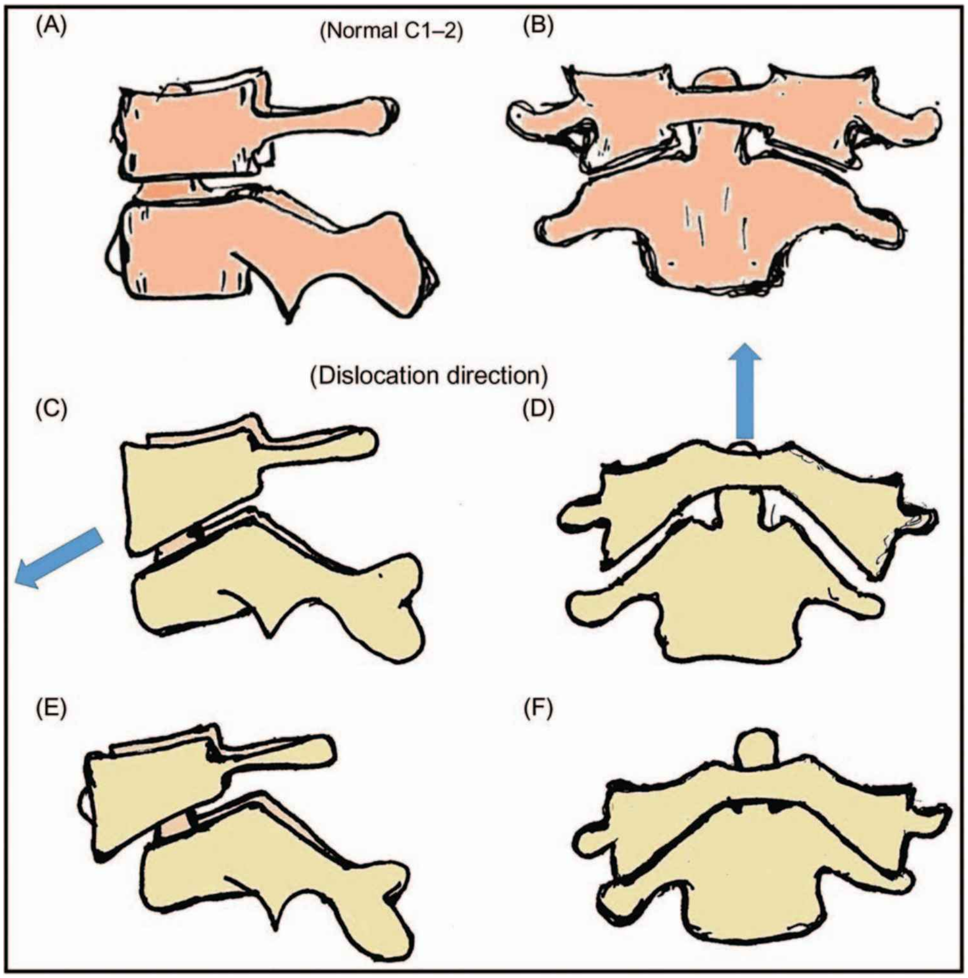

FIGURE 15.13 Asymmetry in atlanto-axial joint.

of atlas and axis, to create a concave surface and reduce dislocation. In some studies, it was advised that managing AAD with techniques like joint surface drilling may cause rotational limitations due to the mechanism of vertical movement of atlanto-axial joint since drilling articular surface means removing the cartilage which has a thickness of around 3 mm. There are also studies indicating that loading may also change the thickness of the articular cartilage modifying the possible movement range. Another form of AAD is the congenital AAD (CAAD). In congenital form of AAD the dislocation occurs mostly due to deformed C1–C2 relation especially through the joint surfaces. Individuals with CAAD have increasingly inclined joint surfaces in both frontal and sagittal planes. Increased inclination causes atlas (C1) to slide anteriorly over the axis (C2) and superior causing a release from dens axis. If we think about daily life, a simple neck flexion to look at a coin a person dropped may simply dislocate that individual's atlas. Aforementioned example is highly probable if symmetrical deformation exists. When there is asymmetrically increased inclination of joint surfaces, dislocation occurs first or more severely on the increased inclination side. This asymmetry may be reflected as rotational movement to the less/not affected side (Fig. 15.13) (Salunke, 2018).

It is well known that not all destructive effects on human body occur swiftly such as trauma. Some happens to achieve their impact on body in long time; such conditions may be referred to as degenerative changes. Degenerative changes in cranio-cervical joint were also investigated in cadaveric specimens and the results were interesting. König et al., indicated that grade III superior articular cartilage degeneration is not present in specimen and may be rare in population too in superior articular cartilage of the atlas, where such high grade degeneration is present in superior articular cartilage of the axis. According to these findings they claimed that atlanto-axial joint has more intense mechanical exposure, which increased at upper joint surfaces. In addition to that previous studies also pointed out to the same result with the proof of thicker cartilage of lower joint surface. It may also have hypothesized that such higher mechanical exposure is due to vertical motion of atlanto-axial joint. König et al., indicated another intriguing finding that indicates higher degeneration frequency at the upper left articular surface of atlas and increased degeneration in the dorsal right and lateral left side in atlanto-axial joint. He also claimed that most of his subjects were right-handed, thus, the instantaneous axis of rotation shifted to non dominant side (Konig et al., 2005).

Along with the effort to reach normal values while determining neck kinesiology, changes in pathological conditions, trauma or post-surgical conditions resulting in surgical stabilization have also been investigated. Previous studies have shown that cervical kinematic values are impaired by surgical spinal stabilization and that the range of motion is reduced. Accordingly, degenerations can develop over time in adjacent segments. Depending on technological progress and the use of disc prosthesis, the classical information about surgical spinal stabilization has started to change. Unlike lumbar prosthesis, surgical technique for cervical disc prosthesis is easier. For this reason, it has been widely used and early kinesiological studies have been published.

The most important problem in trauma is instability. Instability is simply defined as the presence of increased movement of a segment under normal physiological loads. Movements beyond normal ranges or planes may occur due to injured bony or ligamentous structures which normally restrict pathologic movements. As a result, the neural elements inside the spinal column may be damaged. Distortion of the stability can be assessed by radiological examination. The most important problem in a case of instability is the inability to perform kinesiological studies on the unstable spine. Examining the range of motion in a patient with cervical trauma can cause medico-legal problems in case of a newly developing neurological condition, so should definitely be avoided. In trauma patients, degenerative problems related to surgical stabilization in the follow-up or kinesiological changes caused by surgical stabilization are more important. Fusion is the most preferred surgical method to treat the cervical instability in trauma patients. However, fusion is also a pathological condition and adjacent segment degeneration is the most frightful condition of cervical fusion surgeries.

Fusion of the affected disc space is still the most frequently preferred surgical method in the treatment of most cervical pathologies. Fusion surgery somehow tries to treat pathology by creating another pathological condition. In patients who have been treated with fusion surgery, the pain is significantly reduced at the expense of losing segmental movement at the affected level. Sagittal planar movements are less reduced while almost half of the neck rotation movement is lost in occipito-cervical fusions. In subaxial cervical fusions there are limitations in sagittal and lateral bending movements. The increase in number of the segments fused also increases the restriction of the range of motion available (Lin et al., 2014). However, it has not been shown that this limitation adversely affects functional outcomes. Adjacent segment degeneration may be seen in long term follow-up. Limitations of the segmental motions of cervical vertebrae may lead to stress concentrations in adjacent motion segments. Facet joint hypertrophy and early disc degeneration may occur. Excessive forces may lead to widening of the vertebral body and marginal osteophytes may be seen. In some cases spinal canal narrowing caused by cervical fusion surgery in long term follow-ups may be detected. These patients may require the extensive surgeries if neurologic deterioration is developed.

Instability is the second problem of fusion surgeries. Increased motion at the adjacent motion segment may lead to facet joint capsule laxity. Sagittal plane alignment and maintaining the cervical lordosis in initial operation is essential to prevent instability or adjacent segment degeneration. Posterior ligamentous complex of cervical spine especially in upper part of surgical area should be identified and protected carefully. Disruption of posterior ligaments lead to loss of cervical lordosis and the result is cervical kyphosis. Intra-discal pressure of subaxial cervical spine increases in sagittal malalignment of cervical region. Even though the stability is paired with axial load in spine, variety of other loading patterns such as; forward, backward, lateral bending, rotation, shear forces are present. It was mentioned that stability of cervical spine includes numerous factors like; muscle force output, anatomy and alignment of vertebrae in addition to the position of facet joints. There are a couple of considerations on this subject. The first one is the disruption of soft tissues that covers facet joints. This disruption may have two effects depending on the magnitude of the impact. If the impact is low, disrupted tissues will retain some damage and micro tears, which will not affect loading immediately or dramatically but will speed up degenerative process, thus adding to the vicious cycle of more degeneration-less stability and more load (Diagram 15.1). Result of aforementioned low impact disruption of apophyseal joint capsule in the long run will be similar to high impact disruption. No matter the intensity of impact or stress on apophyseal joint capsule or other soft tissues around it, the tissues will eventually lose their load carrying capacity, in other words their ability to form and support stability, thus whole segment starts to bear higher loads resulting in abnormal loading of the whole spine.

Chronic neck pain is a common problem in society. The incidence increases with age. In chronic neck pain, restraints can often be seen at varying rates in neck movements. In addition to limitation of movement, it has been shown that the maximum speed of movement and the rate of acceleration decrease significantly (Dvorak et al., 1988). However, the correlation of angular velocities and

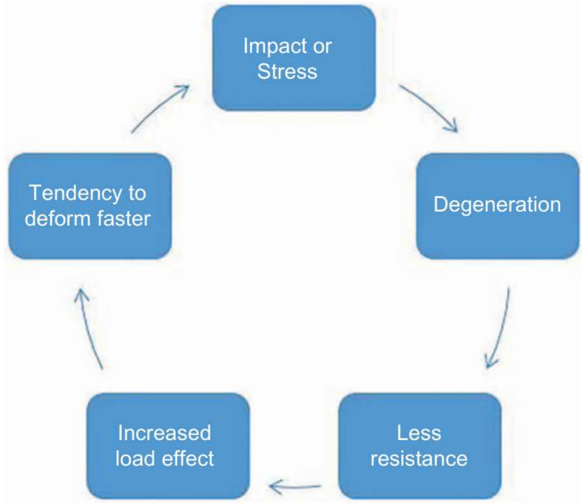

DIAGRAM 15.1 Vicious cycle of degeneration.

changes in acceleration rates with etiologic factors is unknown in patients with chronic neck pain. Bahat et al., compared the kinematic measurements of cervical spine with subjective measurements such as severity of pain, limitation and fear of motion on 25 patients with chronic neck pain (Persson et al., 2007). They aimed to emphasize the clinical significance of the investigated parameters. As a result, they found that kinematic measurements were most affected by fear of movement. In their study, they showed that the severity of pain and limitation of movements did not equally affect the kinematic measurements. However, correlations between the data obtained in the study and each other were moderate.

Neck pain in elderly generally is generally seen due to degenerative changes in facet joints and intervertebral disc space. Facet joint arthrosis is a stable condition. Marginal osteophytes are common and these osteophytes limit the motion of the spine in all directions. However, rotational movements are generally protected. Neck muscles may become atrophied in time with motion restrictions. That is why pre-operative physiotherapy programs include neck muscle strengthening exercises which are critical in older patients with degenerative spine problems.

Features of trapezius muscle were discussed in previous headline however it also have another clinical importance although it is not primarily related to cervical spine. Due to its cranial innervation (accessory nerve-XI) paralysis of this muscle shows peculiar symptoms and is used for neurological evaluation. In the presence of trapezius muscle paralysis the head of the humerus cannot be hold in place and shifts inferiorly, additionally inferior angle of the scapula protrudes during shoulder flexion and abduction. To function properly trapezius muscle also needs longus capitis and longus collii muscles to stabilize the head and cervical spine since these muscles are the antagonists of trapezius.

Multifidi muscles lie along whole spine and will also be discussed in the next chapter. Apart from thoracic and lumbar parts, cervical multifidi muscles originate from directly the capsule of apophyseal joint capsules, thus the cause of neck pain may be explained with problems of cervical multifidi and its disrupting effects such as increasing tension in the joint capsule and/or causing malalignment of the apophyseal joints (Anderson et al., 2005).

Another cause of neck pain is the spasms of neck muscles especially levator scapula. Considering its insertion on scapulae mentioned before, this muscle has functions other than elevating scapula. One of this function is that it laterally flexes and rotates cervical region and the other one is to support the scapulae to be fixed in place during various activities. To understand clearly one may consider a person carrying a bag of groceries in his/her hand. During such activity weight vector goes down from shoulder joint thus depressing the scapula downward where levator scapula needs to contract with other muscles to hold scapula in place. Therefore, prolonged effort in this muscle causes it to become spasmatic and leads to decreased movement of cervical region of the spine in addition to neck pain that radiates through base of the skull.

As mentioned previously, sub-occipital muscles -while contracting bilaterally- extends the skull on the cervical spine however their main function is found to be resisting anterior tilting and kyphotic posture by extending skull. Therefore, in the long term these muscles may become spasmatic and/or weaken that leads to pain and trigger points on muscle. It was mentioned that the pain related to spasmatic sub-occipital muscles may be explained as during prolonged spasms, muscles become stiffer and shorter thus altering the angle of force vector, which leads to increased compression forces on facet joints.

Cervical disc arthroplasty has been developed to resolve the segment disorders and to protect the segmental movement at the affected disc space. Initially, the prosthesis was thought to provide long-term motion, but as the clinical results were being taken, the prosthesis motion did not seem to last very long. Fusion can develop over time in cervical disc arthroplasties and cannot fully meet the expectations in cervical kinematic measurements (White and Panjabi, 1990). It has been shown that the center of rotation in the cervical region in total disc arthroplasty displaces posteriorly during movements (White and Panjabi, 1990). This change is most obvious at C4–5 level. However, the effect of this change on patient satisfaction and especially on the adjacent segment is still controversial.

Trauma may occur due to low intensity cumulative impacts or from a high impact instant injury, yet both have similar effects on the structures of the body. Previously it was reported that prolonged low intensity trauma creates degenerative effects on spine however, there are more high impact trauma types that occur commonly and forms disability. Car accidents may be accounted as one of the most common type of high impact traumas. The trauma occurs when a car crashes another car or some kind of a barrier. At that instant the neck and the skull of the individual tend to continue its movement forward due to inertia and flexes forward but after the impact the velocity reaches zero initiating a reverse acceleration and the neck quickly extends backwards. This specific trauma is called whiplash injury of the neck. High impact extension motion during whiplash injury may cause tears of longus collii and longus capitis muscles, which are referred to as deep neck flexors, and the stabilizator muscles of the cervical region. Clinical symptoms may be seen as the patient is unable to flex forward and lift his/her head from bed while lying in supine position or describes pain during palpation of these muscles.

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Chapter 16

Kinesiology of the thoracic vertebral column

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Introduction

The thoracic region, unlike the cervical and lumbar regions, does not contribute much to trunk movements. The range of motion between the particular segments of thoracic vertebrae is limited. The limitation is due to the fact that there are more ribs and sternal connections than articulations between vertebrae. Ribs attached to each vertebra also articulate with sternum at the front. This creates a closed area in the thoracic region that resembles a birdcage. The most important task of this cage is to protect the vital organs inside the thoracic cavity. At the same time, there is also an expansion feature that permits an average of 14–16 breaths per minute.

Functional anatomy

The thoracic spine consists of 12 vertebrae. T1–T11 vertebrae are similar to each other visually, but they increase in size as they go from cranial to caudal. T12 resembles the lumbar vertebrae more than the thoracic. All thoracic vertebrae form a kyphotic angle anteriorly named as thoracic kyphosis. Thoracic kyphosis can be defined as the angle between the line parallel to the upper end-plate of T1 and lower end-plate of T12. Angle of normal thoracic kyphosis ranges between 20° and 50° (Fig. 16.1). Unlike the cervical spine, the corpus of the upper thoracic vertebrae is more triangular in shape ventrally; however, it becomes more cylindrical caudally. The most important differences of the thoracic vertebrae are the transverse processes that are located at each side. The transverse processes extend laterally and posteriorly. Anteriorly they have a large joint surface, which articulates with the ribs (Fig. 16.2). These costovertebral joints have strong costotransverse ligaments which further restrict movement in this joint. The costovertebral joints move very little in the frontal plane to support the respiration, but at the same time to prevent excessive expansion of the rib cage.

Facet joints in the thoracic region are located on the frontal plane. Sturdy joint capsules markedly constrain extension movement. Facet joints are the only synovial joints in the thoracic region. At the front, there is an intervertebral disc between the corpi. Cellular and chemical properties of the thoracic vertebrae resemble cervical and lumbar ones; however, the size is larger than the cervical. Both the diameter and the height of the vertebrae increase in size, as it gets closer to the thoracolumbar junction. The main task is to compensate the axial loads.

The major ligaments in the thoracic region are anterior longitudinal ligament, posterior longitudinal ligament, supraspinous ligament, interspinous ligament and ligamentum flavum. Ligamentum nuchae in the neck continues as a thick band over the spinous processes when extending to the thoracic region and a thin part forms the interspinous ligament between the spinous processes. Supraspinous ligaments restrict excessive flexion of thoracic vertebrae. Another important ligament posteriorly is ligamentum flavum between two laminas. Unlike other ligaments, it is quite flexible, stretches during flexion and relaxes in extension. Anterior and posterior longitudinal ligaments located in the anterior and posterior parts of the corpus restrict excessive extension and flexion, respectively. The posterior longitudinal ligament forms the anterior wall of the spinal canal. The middle part of the thoracic spine (T6) is the narrowest part of the spinal canal.

The thoracic spinal muscles can be examined in two groups. The first group is the primary back muscles, which originate from a spinal level and insert at another

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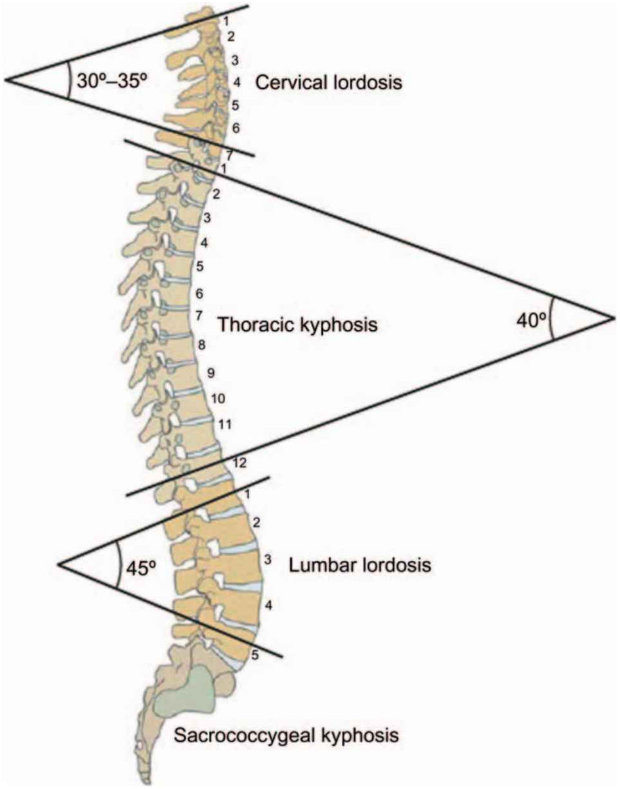

FIGURE 16.1 Lateral view of spine and curvatures.

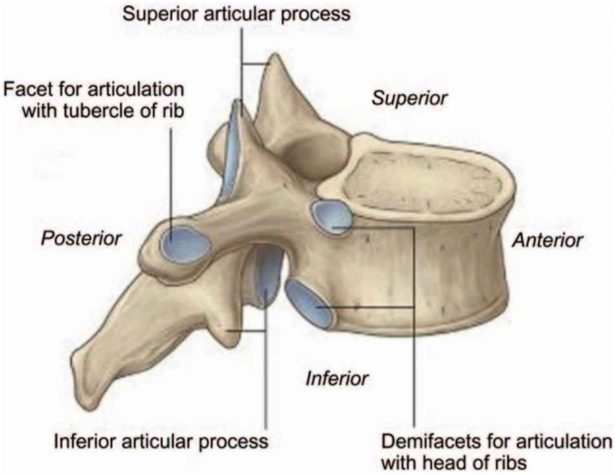
Superior articular process
Facet for articulation with tubercle of rib
Superior
Posterior
Anterior
Inferior
Inferior articular process
Demifacets for articulation with head of ribs

FIGURE 16.2 Articular faces of thoracic vertebrae.

spinal level. Although all primary back muscles are found in the dorsal region, some extend from the cervical to the thoracic region. These are splenius cervicis, semispinalis cervicis, longissimus cervicis and iliocostalis cervicis muscles. Spinalis thoracis, longissimus thoracis and iliocostalis lumborum muscles are located in the middle and lower thoracic regions (Figs. 16.3, 16.4, 16.5). These muscles are responsible for maintaining erect posture of the body. At the same time, they are essential for trunk extension. Unilateral or bilateral paralysis of these muscles may lead to spinal deformities such as neuropathic scoliosis. Multifidus muscle is another primary thoracic spine muscle and lies between the basis of spinous processes and transverse processes (Fig. 16.6). Additionally, there are also rotatory muscles placed between the transverse processes. Multifidus and other rotatory muscles are responsible for trunk rotation.

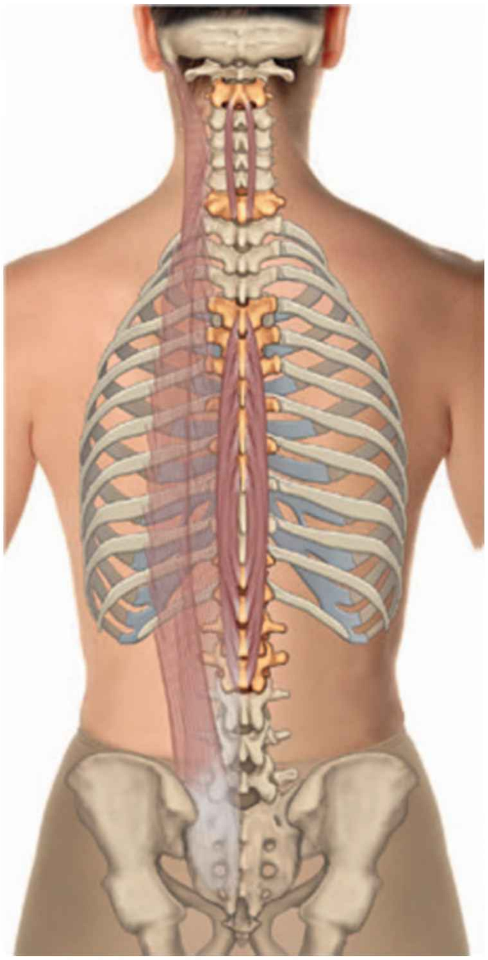

FIGURE 16.3 Spinalis muscle group from posterior view.

The other group is the auxiliary back muscles. These muscles are intercostal and scapular muscles which indirectly affect the spine. The auxiliary group muscles are trapezius, levator scapula, latissimus dorsi and periscapular muscles. Latissimus dorsi muscle primarily extends and adducts the arm. Its distal origin starts form the dorsolumbar fascia and ilium. This muscle helps to maintain sagittal posture of the spine (Fig. 16.7). Auxillary back muscles are primarily responsible of indirectly providing arm movements by maintaining scapular orientation. They also help to maintain proper spinal alignment during postural activities.

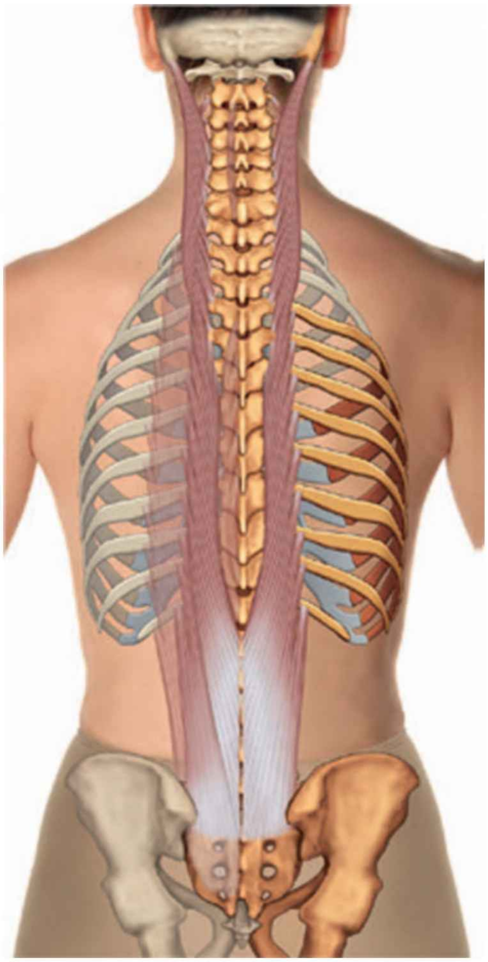

FIGURE 16.4 Longissimus muscle group from posterior view.

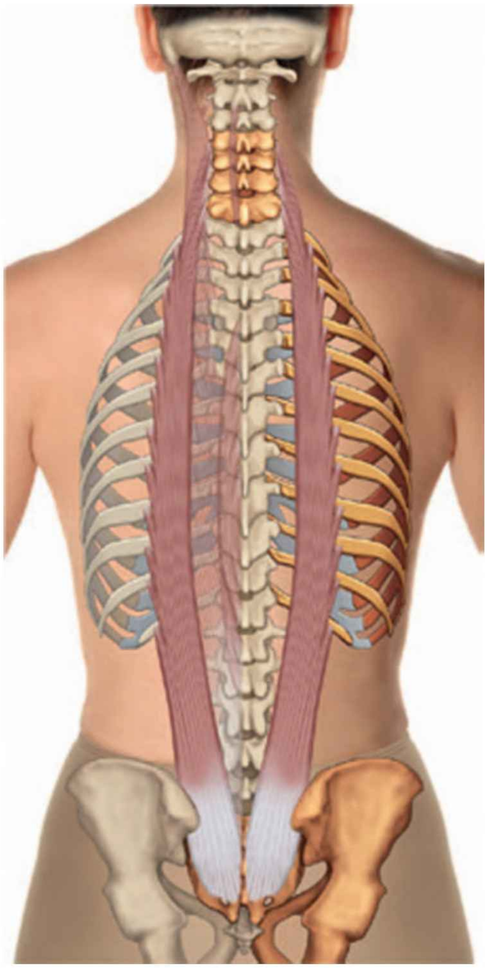

FIGURE 16.5 Iliocostalis muscle group from posterior view.

Kinesiology of the thoracic vertebral column

Kinematics of thoracic vertebral column

Unlike the kinematic studies related to cervical and lumbar regions, studies that examine the kinesiological properties of the thoracic region are scarce. Possible reasons for this are that the movement of the thoracic spine is limited, the traumatic and degenerative pathologies are less than the lumbar and cervical regions and the motion measurements are not easy. Thoracic region kinetics were first investigated by in-vitro methods in cadaver studies (White, 1989). However, in cadaver measurements, the action of ribs, muscles, and perhaps most importantly ligaments are ignored. Additionally, involvement of the rib cage in respiration can also affect measurements. For this reason, cadaver studies may give an idea about changes in normal or pathological conditions, but they do not provide in-depth analysis. Radiographic studies have also been performed for thoracic kinematic features (Edmondston et al., 2012; Fujimori et al., 2014). In these studies, range of motion and segmental movements were examined. The problem in radiographic studies is mostly related to the upper thoracic region. In the upper thoracic region clear radiographic images may not always be obtained, especially due to the superpositioning of the scapula and shoulder joint complex. Dynamic kinematic properties are also difficult to investigate.

In recent years, motion analysis and motion capture technologies have been used for assessing kinematic properties of the thoracic region (List et al., 2013; Ignasiak et al., 2017). These methods are mainly based on tracking reflective markers on the skin. The kinematic data obtained during desired movements are processed using a computer. Thus, range of motion and segmental movements as well as motion speed and end-point excursions can be examined. The most important problem in using the data obtained from these methods is that the markers placed on the skin may sometimes superpose, obscuring each other. Although the validity and reliability of measurements are shown in acceptable ranges (Ignasiak et al., 2017),

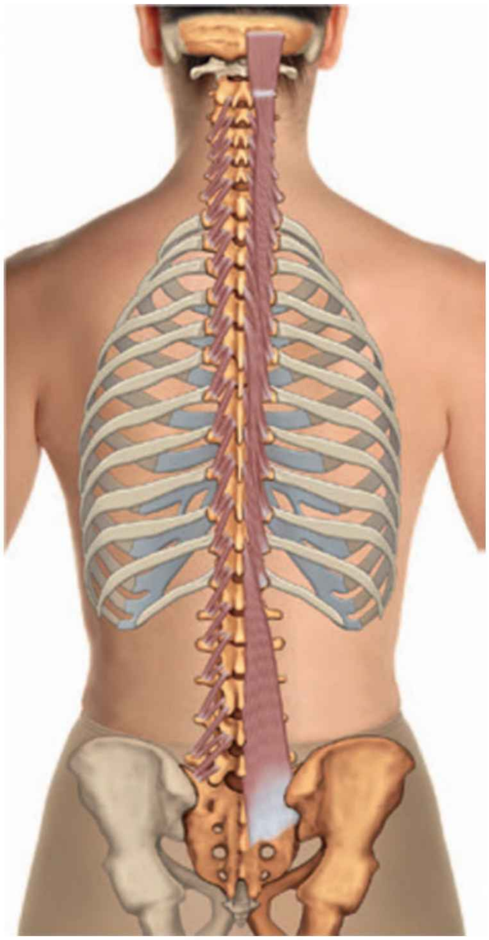

FIGURE 16.6 Multifidus muscle group from posterior view.

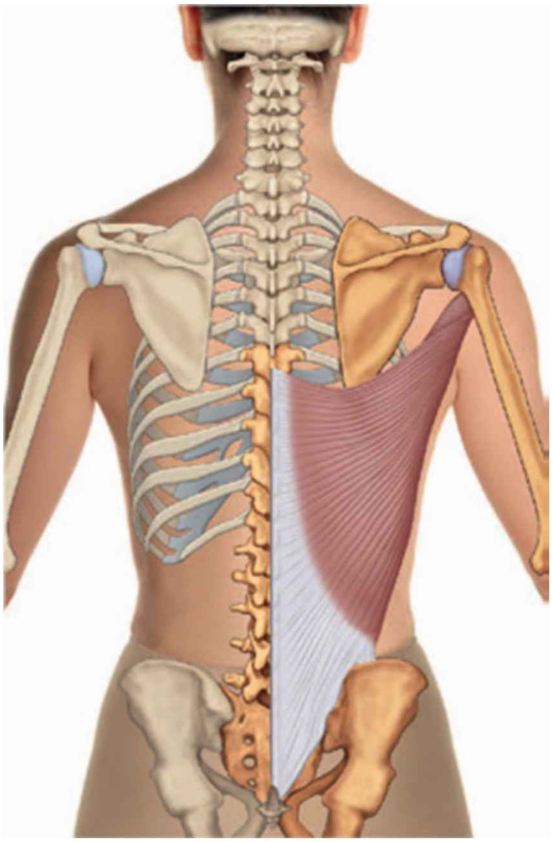

FIGURE 16.7 Latissimus dorsi muscle from posterior view.

the skin and muscle movements during trunk movements can still change the location of the markers.

Considering lumbar and cervical regions, thoracic region may be considered as the most restricted segment of the entire vertebral column. The main reason for this restricted motion capacity is the architectural design of costae and their articulations with the vertebrae. A costo-corporeal joint is formed by semi-articular facets on adjacent vertebrae and the head of a costa and; a costo-transvers joint is formed by the transvers process of a vertebra and the articular tubercule of a costa. These joints create a junction between vertebral column and thoracic cage to support and protect vital internal organs in addition to providing stability to thoracic region. The effect of this stability may be understood by examining lower thoracic vertebrae, specifically T11 and T12 which lack costo-transvers joints. That is why this segment is called thoraco-lumbar junction or segment as it structurally resemble more of lumbar vertebrae rather than thoracic vertebrae.

The most restricted movements of the thoracic region are flexion and extension. In the sagittal plane, the average movement in a motional segment is 4° in the upper thoracic, 6° in the middle thoracic, and 12° in the lower thoracic and thoracolumbar junction regions (White, 1989). On the other hand, lateral bending movement for a motional segment is about 6° in the upper thoracic and is about 8° for lower thoracic region. As for rotation, the situation is somewhat different. In the upper thoracic regions, a motional segment can move about 8°, but towards the thoracolumbar junction, this movement range decreases to about 2° due to anatomical restrictions of the facet joints (Gregersen and Lucas, 1967).

Persson et al. measured the cervical and thoracic spinal movements in the sagittal plane with two-dimensional optoelectronic measurement system in mature female subjects (Persson et al., 2007). According to their results, in sitting position 30% of overall head excursion occurs at the cervicothoracic junction and 10% at the thoracic spine during flexion and extension movements of the neck. Their results also expressed the importance of evaluating cervical spinal motions along with the thoracic region during clinical evaluation of the neck mobility. A similar study is published by Tsang et al. who studied cervicothoracic kinematics in three planes; sagittal, frontal and transvers (Tsang et al., 2013a,b). Their results showed that the upper thoracic spine contributes significantly to overall neck mobility in three planes.

There is no significant difference regarding the amount of contribution to movement between the segments in the thoracic region. In other words, all segments contribute evenly to the entire range. This feature is more obvious especially in flexion-extension. For this reason, the movement of the thoracic spine in flexion and extension does not have a peak at the end ranges. The sagittal plan movement of the entire thoracic spine takes place in a wide-angle motional arc. At the thoracolumbar junction, the movement properties are more similar to lumbar vertebrae. In this segment, the flexion and extension range of motion is wider compared to upper and middle thoracic vertebrae. Ignasiak et al. have studied the kinematic properties of the thoracic spine by two dimensional motion analysis comparing healthy young and healthy 65 years old individuals (Ignasiak et al., 2017). As a result, they found that the onset of flexion and extension movements in younger individuals is mainly in the lower thoracic and thoracolumbar junction regions. The middle and upper thoracic regions are involved later in the flexion movement. In the elderly group, all thoracic segments were shown to participate in the same amount in both flexion and extension movements.

Kinetics of thoracic vertebral column

Thoracic spine may not be explained without ribs since these are the structures that limit the movement of thoracic spine and create coupling motion as a result of unique deviation of them during ventilation. Although it was explained that thoracic spine extends during inspiration and flexes during expiration, additional rotational movement of ribs should also be considered.

During trunk flexion thoracic vertebrae also flex accordingly. During these motions, thoracic vertebrae also translate forward and compress each other. To understand the motion of thoracic vertebrae during flexion better, consider the motion of coupling ribs as their sternal end tilts downwards while rotating inferior. Posterior longitudinal, supraspinous ligaments, ligamentum flavum and anterior part of vertebral discs limit flexion. During extension movement, inferior surface of the superior vertebra translates coupled ribs backwards thus rotating sternal ends of ribs upwards and vertebral end downwards, in which inferior facets of the superior vertebra translates inferior-posteriorly. Anterior longitudinal ligament and posterior part of vertebral discs limit extension motion. Lateral flexion of thoracic spine is accompanied by contralateral rotation of vertebrae. Coupling movement of thoracic vertebrae is a result of costotransverse joint planes compared to oblique joint axis seen in cervical and lumbar regions. To clarify, as the person performs lateral flexion to right side thoracic vertebrae rotates to left side while the ribs in right side rotate forward and the ones in left rotate backwards. In the same example to create these rotational costal movements, right facet joints flex and left facet joints extend. Rotational movement in thoracic vertebrae is performed by coupling translation motion to the opposite side of the rotational movement. Again to clarify it, consider a person rotates his trunk to right side; thoracic vertebrae translates left side while rotating to the right side thus, right ribs rotate posteriorly while left ribs anteriorly.

As mentioned before while considering movements of the thoracic spine, it must be considered as a whole with ribs and sternum. Thoracic cage is not a structure that only limits motions of thoracic spine; it helps to support the loads beared by the spine. This supporting feature is sustained through the presence of costotransverse joints that increase the stiffness of thoracic spine as a whole and the locking of thoracic vertebral discs in place to make them to support the loads more efficiently (Watkins et al., 2005; Little and Adam, 2011). Stabilization of thoracic spine can be explained by coupled ribs however this stiff structure is not complete without an anchor—sternum-located in the front. In cadaveric studies, it was shown that by dissecting sternum the mobility of ribs exponentionally increase. This mobility seen especially in flexion and extension movements causes spine to flex more as a whole. In other studies, it was also shown that in individuals with collapsed sternum kyphotic angle was increased (Itani et al., 1982; Chen et al., 1990; Stahlman et al., 1995). Another, and maybe the most important feature of thoracic spine is it's uniquely compatible orientation of facet joints to both transvers and sagittal planes (Lee, 1996). This unique orientation helps thoracic spine to perform motions without "coupling" since their orientation does not limit any motion (Panjabi et al., 1976).

Thoracic spine has numerous muscles which also includes the ones shared with cervical spine. These muscles may also listed according to the layers similar to earlier chapter as latissimus dorsi, rhomboideus, serratus posterior, longissimus thoracis, spinalis thoracis, iliocostalis thoracis, semispinalis thoracis, multifidus, diaphragm, and external intercostales.

Latissimus dorsi is the largest muscle that has wide range of attachments including spinous processes of T7—L5, iliac crest, thoracolumbar fascia, 9th—12th costae, inferior angulus of scapula and intertubercular sulcus of humerus. Even though the most distal part of latissimus muscle is humerus, its function is far beyond than moving the arm. It supports and controls the tension of thoracolumbar fascia. Via its attachments to vertebrae it plays an important role on sustaining kyphotic and lordotic curves of spine. Thus, when humerus is fixed contraction of latissimus dorsi may increase thoracic kyphosis and lumbar lordosis. A clinically important feature of latissimus dorsi is that it may be used to transfer a person from wheelchair to bed or viceversa. While both arms are fixed on the armrests of a chair contraction of latissimus dorsi muscles elevates body and pelvis from the chair, thus making the individual to be easily transferred.

Rhomboid muscles consist of two parts; major and minor. Major rhomboid muscle originates from spinous processes of T2–T5 and ends at inferior angulus of scapula whereas minor rhomboid muscle originates from spinous processes of C7–T1 to the inferior-middle part of medial border of scapula. These muscles mainly coordinate and act on scapular motions yet they also help maintain thoracic kyphosis by controlling the lateral shift of the scapulae.

Serratus posterior muscle is divided into two parts as superior and inferior. Superior part originates from spinous processes of C6–7 and T1–2 and ends at costal angulus' of 2nd through 5th whereas inferior part originates from supraspinous ligament and aponeurosis of T11–T12, L1–3. An earlier study indicated that inferior part is recruited during deep expiration whereas superior part is recruited during deep inspiration (Vilensky et al., 2001), however in another study it was explained that accessory respiratory muscles are recruited and became hypertrophic in the presence of pulmonary dysfunction and diseases. The study showed that during cadaveric examination, they did not find any signs of hypertrophy in both serratus posterior inferior and superior thus, in accordance with other evidence they concluded that these muscles do not have role in respiration due to their lack of hypertrophy in cadavers of chronic obstructive pulmonary disease (COPD) patients (Loukas et al., 2008).

Multifidi muscles originate from the laminae of vertebrae and end at the capsule of facet joints in cervical segments and transverse processes of vertebrae in thoracic segments. Even though these multi segmental and uniquely aligned muscles are classified as extensors of spine in anatomy books, their complex orientation cannot be described with one single motion. Studies put forward that main function of multifidi is to "fine tune" vertebral motions during spinal movements (Anderson et al., 2005). To explain the mechanism during "fine tuning" of vertebrae in detail, studies pointed 3 main features of multifidi. The first feature is pennate alignment of multifidi, the diagonal orientation to their origins and insertions. Aforementioned diagonal orientation causes these muscles to inherit shorter mucle fibers compared to non-pennate muscles, additionally considering the cellular structure, it was indicated that multifidi have twice the stiffness of extremity muscles. Another muscle architectural feature of multifidi is that they have greater passive elastic capacity. The last feature of multifidi is their capability to perform better or in other words "increase their strength" during flexion of spine meaning better "fine tuning" and stabilization during trunk flexion.

Diaphragm –as it is famous for- the only muscle that has its insertion in the center of itself. Diaphragm has attachments to xiphoid process, 7^{th} to 12^{th} costae and vertebrae corpus of L1–3 and their intervertebral discs. Despite being an inspiration muscle, diaphragm may relate to lumbar pain or in most cases the other way around. Having many widespread origins may be problematic for diaphragm and also for respiration. Numerous studies examined the relation between respiration disruptions and low back pain. Janssens et al. concluded that individuals with low back pain experienced significant diaphragm fatigue after inspiratory muscle loading whereas healthy people did not. Their results specifically indicate the diaphragm fatigue also last longer in individuals with low back pain (Janssens et al., 2013). Earlier studies explained that diaphragm increases the stability of spine and trunk by reducing displacement of internal organs and other structures and increasing intra-abdominal pressure. Minimizing the displacement of internal organs and other structures is possible with the help of altering the tension of thoracolumbar fascia. More fascinating result was the finding that trunk stabilization occurs simultaneously with diaphragm contractions but before extremities movements. Related to these results, in another study conducted by Kocjan et al. it is mentioned that during deep active breathing individuals have better static balance and if diaphragm function is somewhat deteriorated or disrupted, maintaining static balance deteriorated (Kocjan et al., 2018).

Intercostal muscles are located in each costal space where external intercostals attach to tubercules of costae and cartilages of costae whereas internal parts attach to sternum, interspaces between cartilages of first 8th costae and costal cartilages of 8th to 12th costae. Intercostal muscles mainly are related to respiration, however their important feature is that these muscles stabilize thoracic cage during trunk movements.

Instantaneous axis of rotation

Changes in the instantaneous rotation axis are less than those in the cervical and lumbar regions, due to restricted motion of the thoracic region. Still some significant changes in the axis of the instantaneous rotation were mostly investigated in cadaver studies. In flexion and extension, the instantaneous rotation axis is closer to the upper end-plate, and shifts toward the lower end-plate portion of the disc space under translational forces (White, 1989). This change may be helpful in assessing instability, especially in traumatic cases. Segmental instability may be more prominent in injured individuals exposed to translational forces.

Thoracic vertebral column in pathological conditions

In clinical practice, the most important conditions that cause deviations from normal in thoracic region are usually related to traumas. Degenerative processes lead to fewer clinical findings in the thoracic than in the cervical and lumbar spine due to low motility. As the costae and the sternum have protective mechanical effects, the traumatic forces have less affect on the thoracic spine. For this reason, huge traumatic forces are required to disrupt the bony structures and due to this fact additional traumatic conditions such as pulmonary or major vascular injuries are seldom seen. In the sagittal plane, the thoracolumbar junction which is the transitional area between almost a rigid and a more mobile region is where the spinal fractures are most commonly observed. Between T11 and the L2 vertebrae, especially the T12 and L1, the flexion moment created by the weight of the trunk is at the midpoint of the corpus. Under uncontrolled flexional forces that overload the corpus, fractures can easily occur with a fracture line reaching in anterior direction as the vectoral direction of the compressive forces remain anterior to the intervertebral foramen and especially towards the intervertebral disc and the corpus. Damage to the facet joints and posterior elements in thoracic trauma is also an important point of consideration. White and Panjabi studied the range of motion by removing laminae, spinous processes and posterior ligaments in a cadaver study (White, 1989). After removal of the posterior elements, they found a significant increase in range of motion, especially in extension. They concluded that the facet joints and the spinous processes limit the extension of the spine. Similarly, there was an increase in rotational movements. This increase in rotation has been attributed to the removal of ligamentum flavum. This information suggests that stability may deteriorate after damage to the posterior elements in a thoracic trauma. Same traumatic effect may also be observed in operational procedures. Especially, in kyphosis surgery, damage to the posterior ligamentous structures during operations may lead to junctional kyphosis. Proximal segments are more prone to create a junctional kyphosis. Proximal junctional kyphosis is not always symptomatic but almost always visible as an aesthetic condition. That's why superior part of posterior ligamentous complex must be protected during a posterior instrumentation surgery.

Another type of trauma related to thoracic region is caused by excessive flexion injuries; mostly falls onto upper region of thoracic spine. This type of injury causes lower part of the body to bend and collapse on the trunk. As mentioned above thorax is relatively rigid with the help of costa-transvers and costo-corporeal joints, thus, excessive flexion moment find its mechanical transmission pathway at the nearest region: thoraco-lumbar junction. As ever, any change of alignment in the facet joints may also contribute to this injury mechanism. Facet joints' alignment is close to frontal plane in the thoracic region which enables lateral movements while limiting flexion-extension. However, in lumbar region, the opposite is present. For this reason, alignment problems will more likely be met by thoraco-lumbal junction. As a result, excessive forces and shear stresses may easily cause tissue damage.

The most important effects of degenerative processes on the spine are observed in facet joints and disc spaces. Osteophytic spikes develop on the edges of the joints. These osteophytic spikes may also occur due to pseudotumor and tumoral calcification (Coumans et al., 2014; Kilincalp et al., 2015). According to the case reports in literature osteophytic formations may cause various problems such as swallowing dysfunction and intracranial hypotension. The facet joint capsule may also thicken and lose its elasticity. Likewise, fluid loss and shrinkage may be present in the intervertebral disc.

Natural alignment of the thoracic spine is in kyphosis, however, in some cases kyphotic angle may increase or decrease as a result of muscle imbalance, poor posture or an underlying pathology. Increased kyphotic angle, especially in older people, may perforate fibrotic disc materials at the edges of the end-plates of vertebral bodies and cause them to protrude into the body (Amoretti et al., 2019). This is a common condition in patients and referred to as Schmorl's nodes. Schmorl's nodes mainly affect axial loading of the spine as these nodes penetrate into vertebral bodies thus reduces integrity of the vertebra. Considering that Schmorl's nodes often occur in patients with fragile vertebral endplate due to traumatic, vascular or degenerative conditions, it may be possible to think that the person also may have altered gait pattern. Additionally, Schmorl's nodes may be associated with chronic back pain. The source of this pain and also aforementioned altered gait pattern is explained as the disc material penetrates through vertebral endplates to vertebral bodies, mimicking pathophysiologic reactions of a fracture. In this case as it would be during a fracture, nociceptors in annulus fibrosus and periosteum are activated thus causing low back pain. Expansion of the vertebral end-plates and osteophytes reduce the load per unit area that results with limited spinal movements. Restricted spinal motion may affect coordination between different spinal segments, thus, it may cause all the alignment problems and result in disrupted motion. Disruption in segmental motion in elder individuals might be attributed to aforementioned facts. There are studies that report that flexion and extension movements are mainly performed by the hip joints in the elderly rather than the spine (Pries et al., 2015; Ignasiak et al., 2017). As the motion between the thoracic spine segments is restricted, the body tilts forward with the effect of gravity during flexion. To counteract this, a flexional moment develops in the cervico-thoracic and lumbo-sacral regions. This moment is fundamentally compensated by two mechanisms. Firstly, the forward flexion is ensured with hip flexion. Secondly, body balance is maintained by the increase in the angle of thoracic kyphosis. Limitation of thoracic spinal segmental movements, development of kyphosis, and increased flexion moment at junctions may explain why development of spinal fractures is most frequent at between T5–T7 and T11–L1 in the elderly (Cooper et al., 1992).

Chronic neck and back pain are common complaints in society. It has been reported that in general it may be seen up to 70% of the population (Cote et al., 2004). In patients with neck and back pain, it is important to evaluate the range of motion and muscle strength in physical examination. For this reason, studies on spinal kinematics have been accelerated in recent years in patients with neck and back pain. Persistent movement limitations, muscle strength reductions can be easily detected by physical examination, but the effects of these findings on etiology and natural history could not be shown in patients with nonspecific neck pain (Sjolander et al., 2008). Norlander et al. studied the mobility of the motional segments between C7 and T5 on 142 male and 139 female subjects (Norlander et al., 1996). In patients with chronic neck pain hypomobility was detected at cervicothoracic junctional region with flexion. At the same time, they found a correlation between C7–T1 flexion hypomobility and age, smoking and years of employment. However, restraint of movement appears to be a result rather than the cause of the underlying pathology. Tsang and colleagues compared asymptomatic subjects with patients suffering chronic nonspecific neck pain in their studies for frontal and axial plane as well as the sagittal plane measurements (Tsang et al., 2013a,b). Kinematic variables such as angular displacement, velocity and acceleration were compared between the two groups. Chronic neck pain group showed significantly decreased cervical angular velocity and acceleration of neck movement. They found decreased control in coordination between the cervical and upper thoracic spines in the neck pain group and the loss of coordination was most apparent in angular velocity and acceleration parameters. They concluded that the evaluation of angular velocity, acceleration and movement coordination instead of assessment of the range of motion of the neck would be beneficial to clinical interpretation of movement dysfunctions.

Scoliosis is another clinical condition that affects whole spine. Even though scoliosis was defined as a three dimensional deformity, the main component -lateral flexion- changes not only axial loading but also muscle lines, positions of articular faces and tension of joint capsules. Such changes occur due to lateral flexion of the spine that is accompanied by rotation and reduced kyphosis. According to the studies that were conducted on patients with single major thoracic curve, trunk rotation tends to be characteristically to the concave side during gait. To be able to explain this rotational motion in depth following example must be put through. In contrast to rotation of trunk during gait, in quiet standing position, trunk rotation is neutralized with the pelvic rotation to the convex side. This alignment positions the trunk straight to the frontal side and pelvis in convex side backwards. For example, lateral flexion of spine comes with axial rotation of vertebrae naturally when examining the segmental motion. Due to this normal kinematic feature costae will also join the rotational movement and create an asymmetrical image of thorax, specifically named as “rib hump”. Such asymmetrical alignment will eventually cause muscles and other soft tissues like ligaments and joint capsules blend in the deformity by altering their form and eventually sending signals to brain as one defines it as pain. To fix this abnormal kinematics and rehabilitate the individual; scoliosis exercises, bracing and surgical techniques are used in clinical setting (Wu et al., 2019).

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Chapter 17

Kinesiology of the lumbar vertebral column

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Introduction

Lumbar spine plays major role in upright posture of the body. It forms a base structure for upper segments. Abdominal organs suspend to lumbar spine with the help of different types of fascii and they are protected indirectly during movements. To achieve this, lumbar spine has strong ligaments and greater bony elements than thoracic and cervical regions. Pelvis, hips and lumbar spine act as a single complex during walking. Different kinematic properties of lumbar motion segments affect sacrum and pelvis, thus walking in harmony can be achieved.

Functional anatomy

Lumbar spine is composed of five vertebrae. Their size increases from cranial to caudal. L5 vertebra is the widest vertebra of all the spinal column. Posteriorly, there are facet joints between two adjacent vertebrae but their motion planes are different from thoracic spine. Lumbar facet joints are oriented in sagittal plane. For this reason, main motion occurs in the sagittal plane; flexion and extension. Although they have tendency to rotate to frontal plane caudally, facet joints of L4-5 are usually located in the sagittal plane with slight obliquity. Only facet joints of L5-S1 are oriented in the frontal plane. Facet joints of lumbar spine are synovial joints covered by joint capsule and synovial membrane.

Vertebral bodies of lumbar spine are bigger than thoracic spine and their end-plates are slightly concave. Trabecular bones of lumbar vertebral bodies are oriented to support axial loads. Thin trabecular bony walls locate perpendicular or oblique to the end-plates to increase the resistance of vertebral body to axial loads (Fig. 17.1). Trabecular bony scaffolds are sparse at posterior one-third part of the vertebral body. This feature may be the reason why a triangular bone piece displaces posteriorly into the spinal canal frequently after vertebral body fractures. Transverse processes are thinner but longer than thoracic spine. There are small bony prominences between transverse process and facet joints bilaterally which are called as mammillary processes. These bony prominences are important for trans-pedicular screw implantation. Spinous processes become wider from L1 to L5 into the sagittal plane. In contrast, laminae are wider in upper lumbar vertebrae, but they get thinner caudally.

Lumbar discs have similar content as cervical and thoracic discs. Annulus fibrosus is pretty thicker compared to upper segments and consists of multiple layers of collagen fibers. The oblique orientation of these fibers (between 45 and 60 degrees) increases their tear resistance (Fig. 17.2). Posterior part of annulus fibrosus which forms the anterior wall of lumbar spinal canal, is the weakest part of lumbar discs. Nucleus pulposus contains disc cells, proteoaminoglicans, heparin sulfate and plenty of water. This material acts as a hydraulic suspension system under compression loads and transmits the load to adjacent end-plate equally. Posterolateral surface of disc forms the anterior border of intervertebral foramina that contains radicular nerves and a special nerve innervating the dura and spinal nerve root called as sinuvertebral nerve.

Supraspinous ligaments, interspinous ligaments, anterior and posterior longitudinal ligaments and ligamentum flavum (yellow ligament) are the main ligaments of lumbar spine. Anterior and posterior longitudinal ligaments are located at anterior and posterior surfaces of vertebral bodies through the spinal column. These ligaments restrict excessive extension and flexion ranges, respectively.

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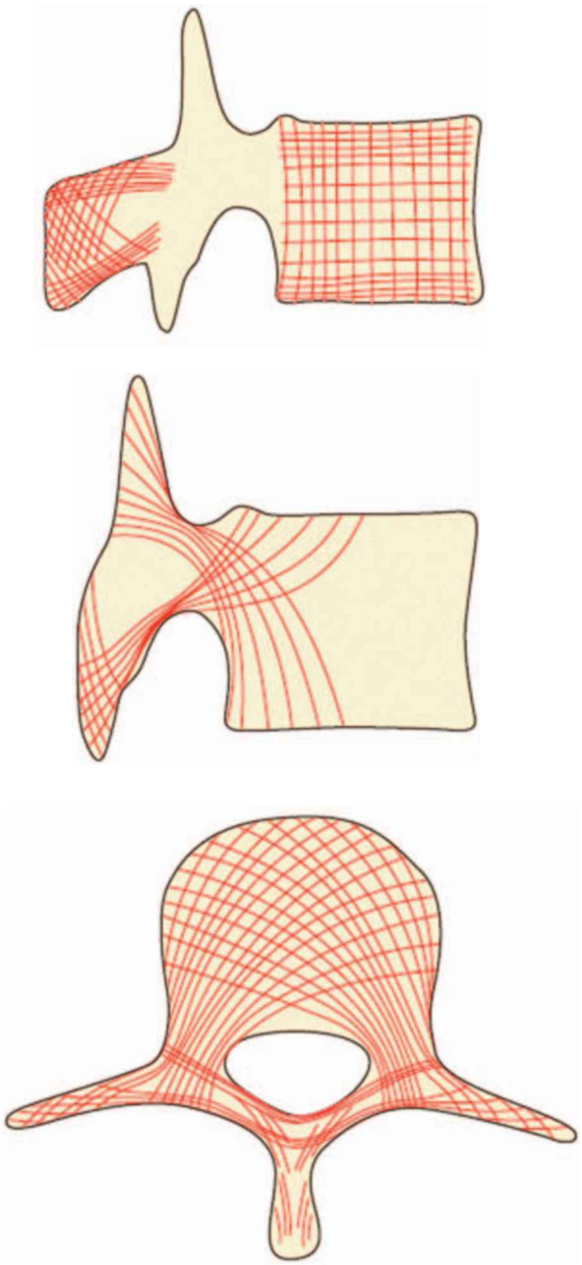

FIGURE 17.1 Trabecular bone architecture of vertebral body. There is a mechanically weak point at the posterior one third of the body because of the alignment of trabecular lamellae.

Supraspinous ligaments, interspinous ligaments and yellow ligaments resist to flexion motion.

Lumbar spine is surrounded by thick and strong muscle bundles. Psoas major muscle originates anteriorly from L1 to L5 vertebral body and disc spaces and attaches to the lesser trochanter (Fig. 17.3). Its vector of contraction is located at anterior and lateral part of the spine. This muscle is a primary flexor of the hip joint. Paravertebral muscles (multifidus, longissimus and iliocostalis) are located at the posterior part of the lumbar spine and the iliocostalis lumborum muscle is the primary erector muscle of lumbar portion (Fig. 17.4). Their contraction creates extension of the body. Abdominal and gluteal muscles are other important muscles for lumbar spine. Rectus abdominis muscle forms anterior wall of abdomen (Fig. 17.5). It flexes the trunk forward when it contracts. There are two oblique muscles at the lateral wall of abdomen and they twist the lumbar spine (Figs. 17.6 and 17.7). Gluteal muscles, psoas and abdominal muscles maintain the natural curvature of lumbar spine at sagittal plane referred to "lordosis".

Kinesiology of the lumbar vertebral column

Kinematics of lumbar vertebral column

The lumbar spine and hip joints are responsible for the mobility of the body. Lumbosacral junction and sacroiliac joints act as a transition zone between lumbar spine and hips. Flexion and extension of the body can be achieved with harmonic combination of lumbar spine and hip movements. Lumbar spine forms the lordosis during childhood and retains it after in a healthy individual. All spinal column remains in kyphotic posture in the newborn period. Sagittal alignment and balance are restored with the initiation of walking. Lumbar lordosis increases with age (Fig. 17.8).

The main motions of lumbar spine are flexion-extension and lateral deviations. Flexion and extension range is approximately 12 degrees at L1-2 motion segment, 15 degrees at L3-4 and 17 degrees at L5-S1 segment (White and Panjabi, 1990). Mean total flexion extension range of motion of lumbar spine is 75 degrees. Intervertebral discs are compressed while the lumbar vertebrae flexes. Intervertebral disc pressure increases with the increased flexion of body (Fig. 17.9). Even though, intra-discal pressure decreases while the lumbar spine in extension (Fig. 17.10). Sagittal plane motion increases from cranial to caudal direction. Lateral bending range is quite limited compared to motion in sagittal plane; it is 6 degrees at L1-2, 8 degrees at L3-4 and only 3 degrees at L5-S1 segment (White and Panjabi, 1990). Total lateral bending range of motion of lumbar spine is approximately 30 degrees. Lumbosacral junction has very limited lateral bending motion and its anatomical properties are the main cause of this limitation. Bilateral facet joints of L5-S1 segment are located in frontal plane. Transverse processes of L5 are very close to iliac spine and superior sacral wall. Lastly, L5-S1 disc space is angulated inferiorly from posterior to anterior in accordance with lumbar lordosis. These features limits lateral bending of L5-S1 segment and adds in sagittal plane range of motion. Axial rotation of lumbar segments is quite similar and average around

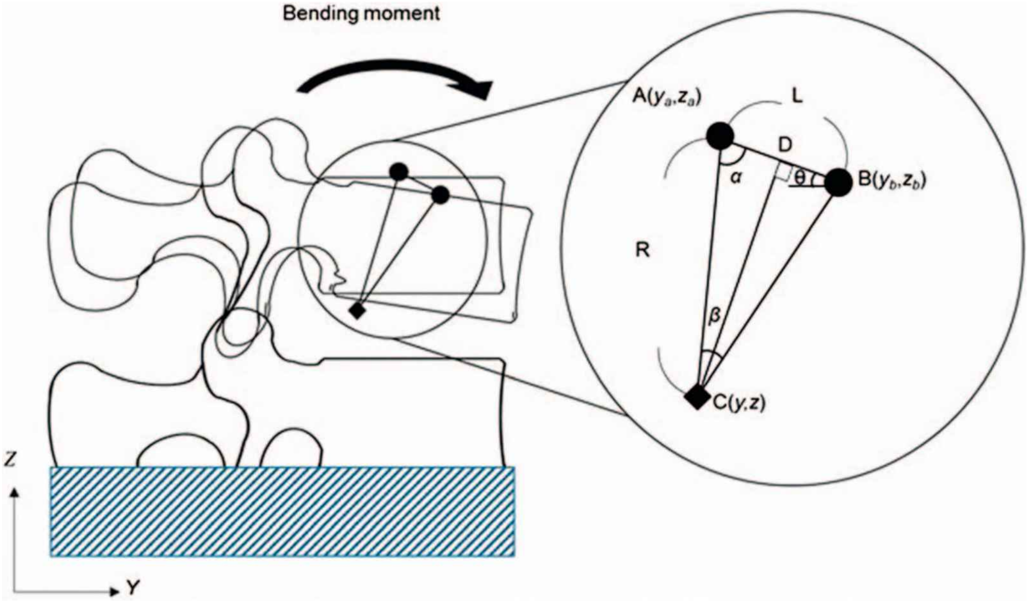

FIGURE 17.2 Instantaneous axis of the spine is located at the posterior one third of intervertebral disc space. Its location is changed anteriorly during sagittal plane motions.

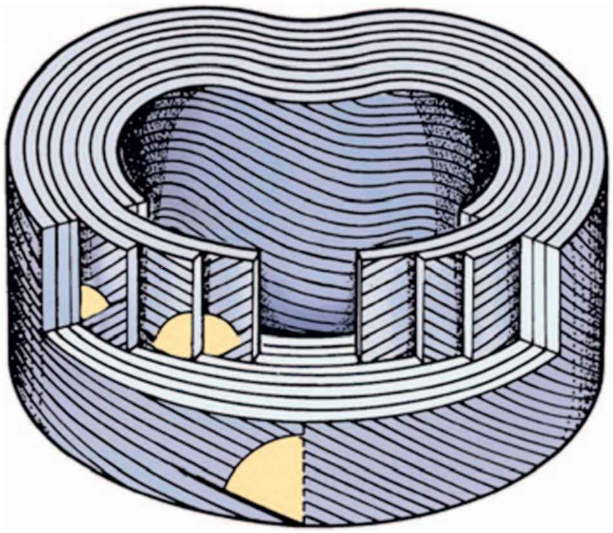

FIGURE 17.3 Oblique orientation of collagen fibers in lumbar intervertebral disc.

2 degrees. Total lumbar spine rotation is 10 degrees (White and Panjabi, 1990). Considering lumbar spine, upper region (L1-L2-L3) usually is counted in thoracolumbar conjunction, since these vertebrae even though differ from those in lower thoracic spine, yet have the similar kinesiological features. However, L4-L5 and especially L5-S1 has unique properties thus granting these segments varying kinematics. The motions of the lumbar spine are very complex. It requires a measurement technique that can record two or three-dimensional movements. Lumbar kinematic measurements are mainly based

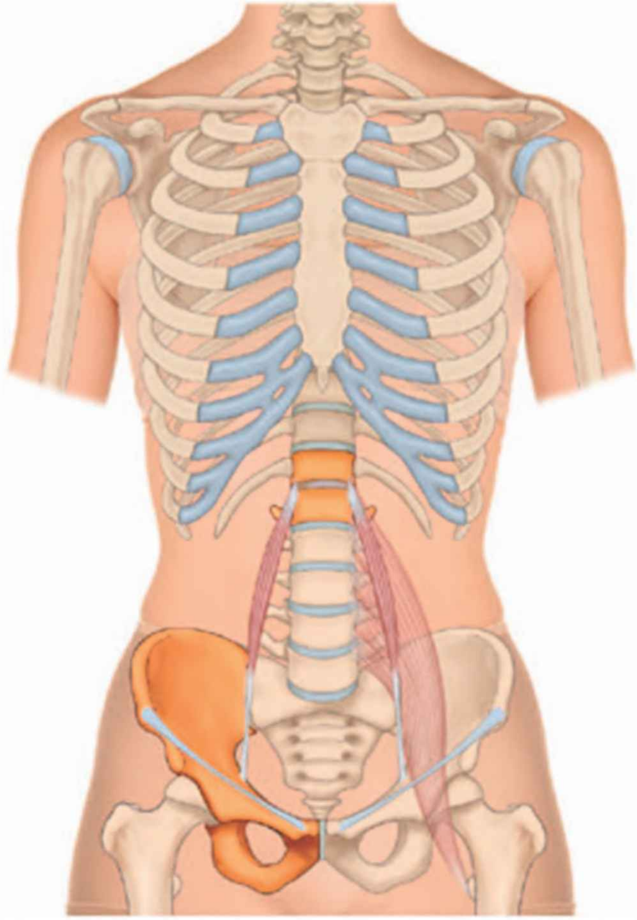

FIGURE 17.4 Psoas major and minor muscles. Psoas major is the main flexor muscle of hip joint.

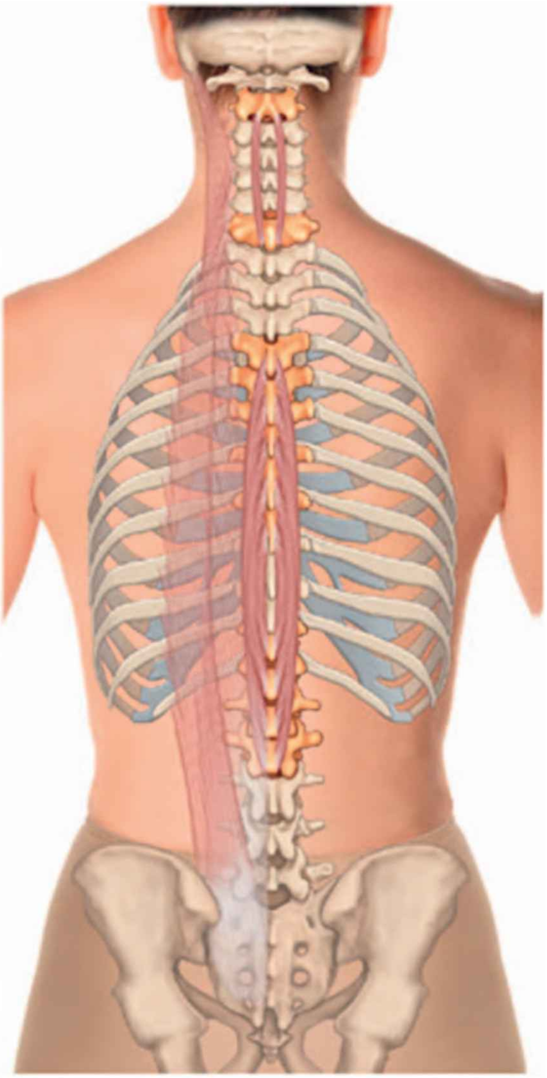

FIGURE 17.5 Iliocostalis lumborum muscle is the primary erector muscle of lumbar portion.

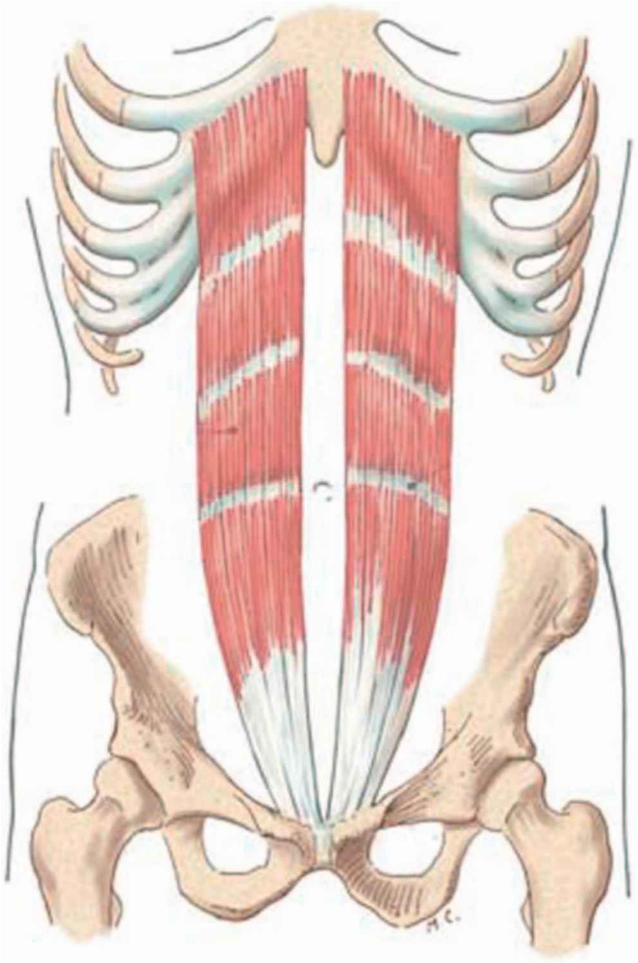

FIGURE 17.6 Rectus abdominis muscle.

on radiographic examinations (Posner et al., 1982; Pearcy, 1985). Radiological imaging is considered to be accurate an technique that can measure inter-segmental movement of lumbar vertebrae, however, radiographic methods carry radiation exposure to the subjects and may be harmful to the patients. Some authors developed computerized analyses techniques and they suggested that it is very easy to interpret the results (Dvorak et al., 1991). In these studies, during flexion and extension marked anterior translations between motion segments were shown. Some authors proposed that more than 2 mm anterior translation is a sign of instability (Pearcy, 1985). But others showed significant anterior translations such as 5 mm can be seen in normal conditions (Dvorak et al., 1991). Electromagnetic tracking systems are alternative approaches to radiographic methods for assessing gait in a clinical setting (Lee, 2002). Spinous processes are marked with markers and photographs or cine-films are obtained during motion or walking. In another technique, metallic wires are inserted into the spinous process of each lumbar vertebrae and three-dimensional motion of lumbar spine is investigated (MacWilliams et al., 2013). This technique has advantages such as it can be applied in dynamic conditions and gives quite precise results, however, this is an invasive method and it is not easy to use in clinical applications.

As a result of growing up, the world of an infant expands. While anatomically preparing him/herself to this expanded world the infant must also require performing new motions with altered spinal column and newly formed lumbar lordosis (Fig. 17.11). Lumbar flexion is required to perform most daily activities such as lacing shoes, picking up objects from ground. Lumbar flexion activities are distinctive, since they are used to displace trunk and head to complete tasks that are required to be performed in lower level of body. Individuals sometimes

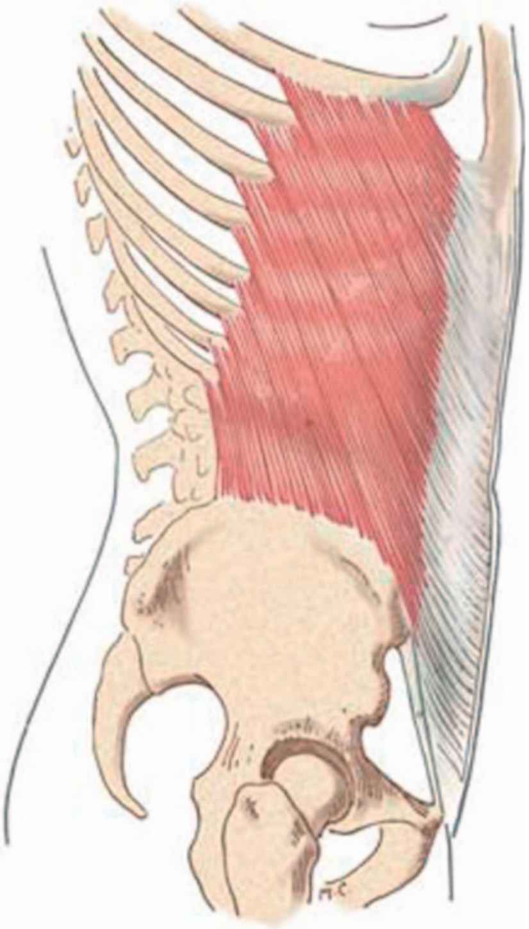

FIGURE 17.7 External abdominal obliquus muscle.

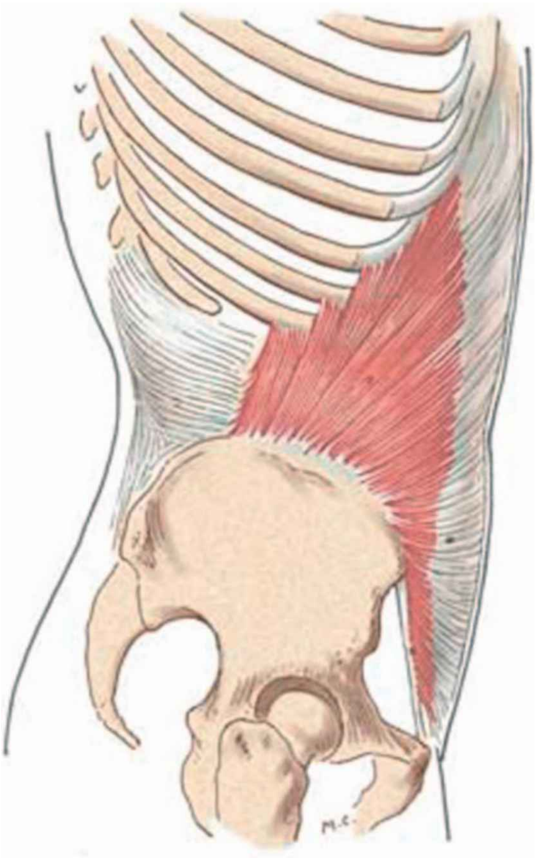

FIGURE 17.8 Internal abdominal obliquus muscle.

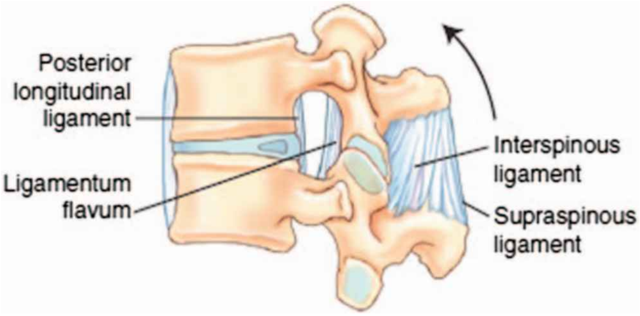

FIGURE 17.9 Discs are compressed in flexion of lumbar spine.

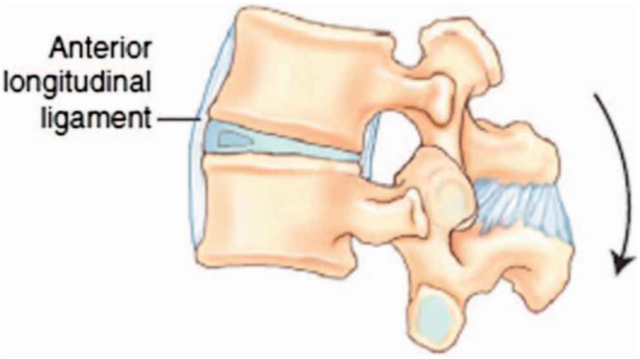

FIGURE 17.10 Disc spaces distracts when the lumbar spine extents.

perform such activities with the assistance of hip and knee flexion, which reduces the load on lumbar region, but the important question is "how people perform such activities with the help of other segments?". During flexion of lumbar region, spine progresses forward and downward, a position that increases the load on anteriorly located structures like intervertebral discs and anterior parts of vertebral bodies. While the load shifts towards these structures, it is also important to identify where it shifts from. The small part of the answer lies in the design of the posterior sides of these structures and facet joints. Facet joints retain load like most of the structures in spine during standing. Yet it transfers some of this load to anterior part of the spine, where compressive forces shift during flexion. Fortunately, this shifting does not continue on till to the end of a movement. As the range of motion increases the capsule of facet joints start to become tighter and they become structures that limit further motion. On the other hand, flexion of lumbar spine increases the volume of the vertebral canal and may relieve the pain caused by a narrowed foramen. As a downside if the

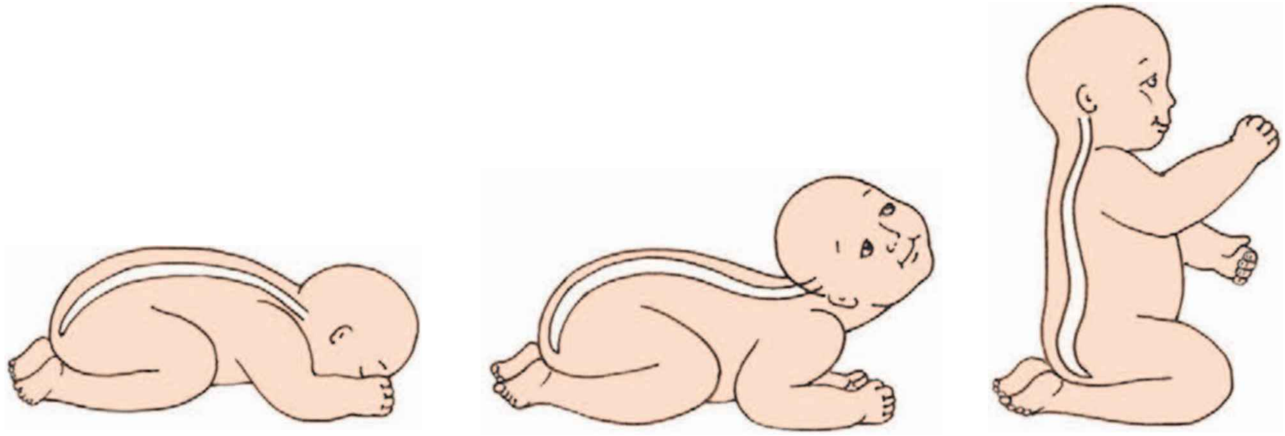

FIGURE 17.11 Sagittal alignment of spinal column. Physiologic curves of thoracic and lumbar spine are restored with the age.

individual has some kind of discal malalignment or a deformed disc problem, flexion of the lumbar region may increase symptoms as the disc will shift postero-laterally and impinges on neural structures. This knowledge is sometimes clinically used to identify the primary cause of low back pain in patients.

Lumbar spine motions can be achieved in three dimensions at the same time. Especially lateral bending is always coupled with axial rotation of a motion segment (Pearcy and Tibrewal, 1984; Panjabi et al., 1989). The orientation of the facet joints and ligamentous connections in the lumbar spine may be the causative factor of this motion coupling. Facet joints play a role of hinge between frontal and axial planes. Thus, lateral bending results in axial rotation and vice versa. The spinous processes rotate toward the concave side and the vertebral body rotates toward the convex side of the curve. This mechanism may be helpful to understand the three dimensional properties of scoliotic curves.

Facet joints are important components of the spine in motion and carries great amount of body weight. They resist almost 20% of body weight in axial loading. Facet joints are synovial joints reinforced with a joint capsule and a synovial membrane lining the inner side of the joint. Joint surfaces are covered with hyaline cartilage. They can easily degenerate due to excess axial loading. Lumbar lordosis increases during standing position which increases facet joint exposure to shearing forces (Fig. 17.12). Facet joint capsule limits excessive flexion movement in the sagittal plane. Inferior articular process of a facet joint is concave and orients in the sagittal plane. This orientation and a tight joint capsule helps to limit flexion (Fig. 17.13). Lumbar facet joints are vertically aligned and angled with the sagittal plane. This position helps limiting rotational movements and explains why lumbar facet joints and their pars articularis tend to retain much of the stress and shear forces during flexion and extension. It should also be noted that during flexion although the load shifts from the facet joints, the pressure increases in the joint capsule. This increase is caused by the reduced contact surface of facet joints. It is plausible to think that the weight in normal conditions usually shift

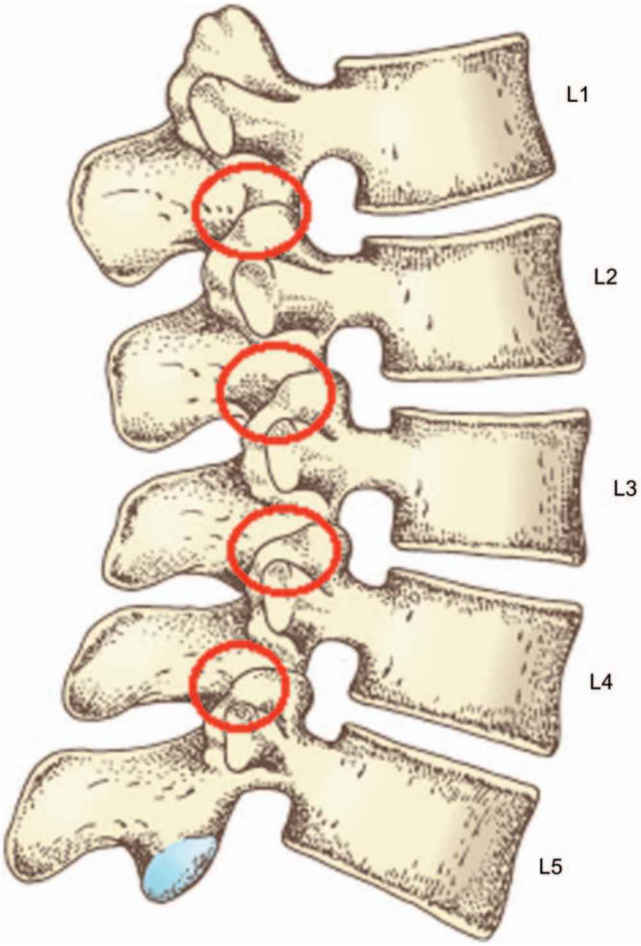

FIGURE 17.12 Facet joint positions during standing and sitting.

to anterior structures, however, the reduction in contact area is greater than reduction in compressive force.

Sacroiliac joints are other important structures of the spine. They link the spinal column to the lower extremities and function as a load-transferring unit. These joints are synovial joints same as facet joints. They have joint capsule and synovial membrane. Joint surfaces of both sacrum and iliac bone are covered by hyaline cartilage. There are thick and strong ligaments at the anterior and posterior parts of sacroiliac joints (Figs. 17.14 and 17.15). Normally there is no motion or minimal rotation below 2 degrees at sacroiliac joints. Some pathological conditions may affect the sacroiliac joints producing excessive motion. Increased motion at these joints can stimuli the nerve fibers of the ligaments and sacroiliac joint pain may occur.

Sacroiliac joints have the ability to perform translational and rotational motions. To define the combination of such motions, researchers created a term of nutation and counter-nutation. Term of nutation is derived from the act of "nodding" which is the motion of head tilting and flexing forward to show that he/she accepts or agrees a statement (Neumann, 2002). Nutation can be explained as the anterior rotation of sacrum on ilium or posterior rotation of ilium on sacrum. Even though it is called "rotation" sacroiliac joint does not have a proper axis of rotation thus "tilting" or "rocking" terms are also used to describe nutation and counter-nutation (Moore and Daly, 2006). Nutation motion of sacroiliac joints helps amplifying stabilization function of sacrum by increasing the tension in the sacro-tuberous and sacro-spinous ligaments, additionally increasing compression on sacroiliac joint surfaces.

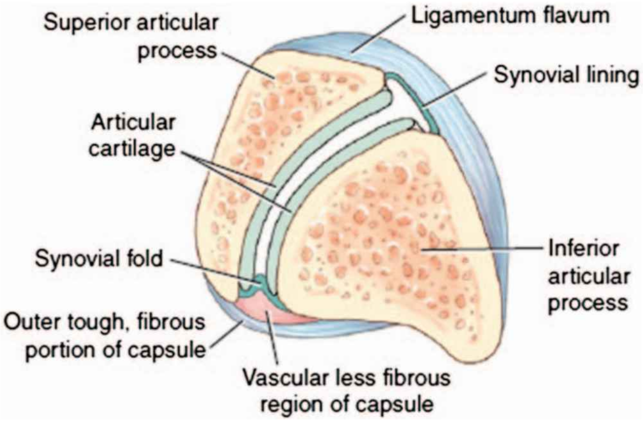
Superior articular process
Ligamentum flavum
Synovial lining
Articular cartilage
Synovial fold
Inferior articular process
Outer tough, fibrous portion of capsule
Vascular less fibrous region of capsule

FIGURE 17.13 Joint capsule and articular process orientation of facet joints limit the forward bending of lumbar spine.

Coccyx is a formation that alters during first few decades of a lifespan. It starts its journey as a segment that contains numerous vertebrae (10—12th vertebrae) however most of them are removed while remaining vertebrae fuse together to form the coccyx. It was shown that vertebrae of coccyx contain vertebral discs yet those disappear during vertebral fusing around 2nd and 3rd decade. Although it is fairly small, coccyx forms a base for attachment to many structures like ventral sacrococcygeal ligament, coccygeal muscles, sphincter ani externus, lateral coccygeal ligament, gluteus maximus muscle.

Kinetics of lumbar vertebral column

Lumbar spine surrounded by complex muscle groups. Abdominal muscles and psoas muscles are located anteriorly and whole body and lumbar spine flex when they contract. Internal and external oblique muscles help to rotatory muscles of the spine, which are located between transverse process and spinous process. Both of them maintain axial motions. Paravertebral muscles extend the lumbar spine and maintain the erect posture of the body.

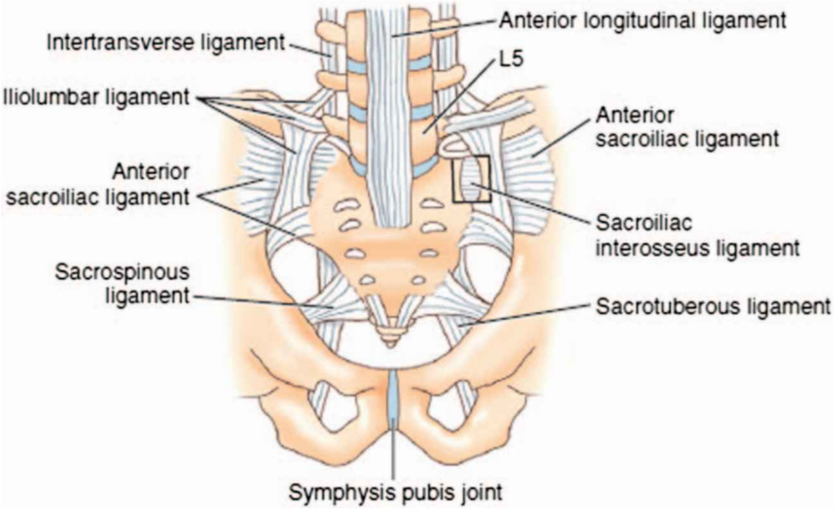
Anterior longitudinal ligament
Intertransverse ligament
L5
Iliolumbar ligament
Anterior sacroiliac ligament
Anterior sacroiliac ligament
Sacroiliac interosseus ligament
Sacrospinous ligament
Sacrotuberous ligament
Symphysis pubis joint

FIGURE 17.14 Anterior aspect of sacroiliac joint ligaments.

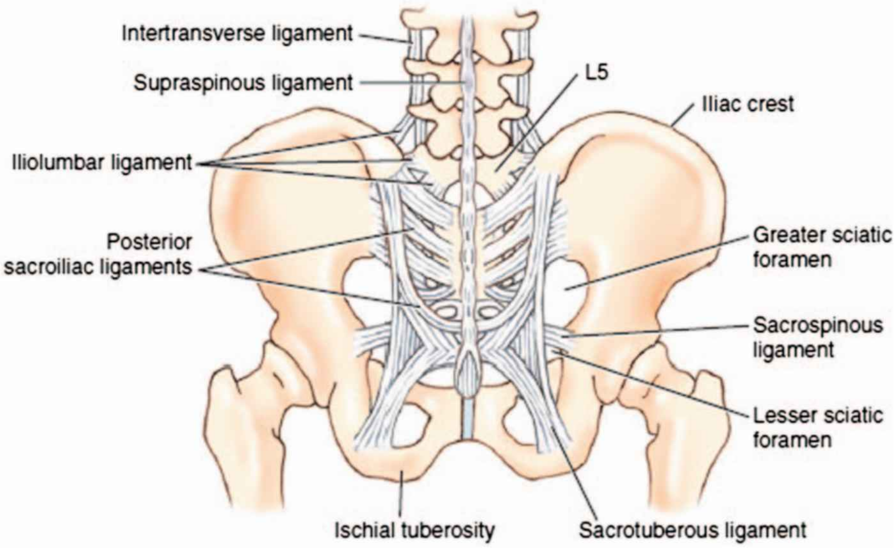

FIGURE 17.15 Posterior aspect of sacroiliac joint ligaments.

Gluteus maximus muscle is the primary determinant of sagittal pelvic alignment. Pelvis turns retroversion (posterior rotation) when it contracts. This muscle also is very important to forming and maintaining the lumbar lordosis. Normal lumbar lordosis is between 20 and 50 degrees. If there is any radicular root compression at the level of intervertebral foramina, gluteus maximus muscle may contract as a compensatory mechanism. As a result, lumbar lordosis decreases or flat back can be achieved. The term "decreased lumbar lordosis" may be understood as intervertebral foramen widening. In this way, compensatory mechanisms can minimize the root compression and diminish the pain by controlling lumbar muscles.

Erector spinae muscles are located longitudinally along the spine and perform extension movement. Unlike cervical and thoracic regions lumbar region only has one erector spinae muscle: ilicostalis lumborum muscle. Iliocostalis lumborum muscle attaches spinous processes, sacrotuberous and sacrospinous ligaments of the vertebrae from T11 to L5. It also attaches to posterior sacroiliac ligament, posterior-medial iliac crest costae from 6th to 12th. It also laterally flexes lumbar region in addition to extension. Erector spinae muscles create posterior shear forces compensating for the anterior shear forces caused by iliopsoas muscle, lordotic posture and gravity.

Multifidi – as explained in the previous chapter – extends the spine, however, when contracted bilaterally they also create a compression force stabilizing the lumbar spine (Sahrmann, 2002) Yet, their most important function is to compensate the anterior shear force during flexion movement of the spine. Another important function of multifidi is that during axial rotation they contract to neutralize slight flexion motion. With the help of this neutralization action of multifidi during axial rotation the motion becomes smooth axial rotation and not rotation and slight forward flexion (Middleditch and Oliver, 1991; Porterfield and DeRosa, 1998).

All of the muscles mentioned above are well-known since their function and/or size overshadow the others. Intertransversarii lumborum muscles are such a group of underestimated muscles. These muscles are located between transverse processes of adjacent vertebrae (Middleditch and Oliver, 1991). Intertransversarii muscles in lumbar segment stabilize the adjacent vertebra during lateral flexion. Additionally, these short muscles tend to contain more muscle spindles compared to their deeper counterparts, thus, they are considered to work as proprioceptive beacons that enlighten the path to postural control and spinal fine tuning.

As cervical spine contains muscles that originate from skull yet have effect on spine, lumbar region also contains muscles that originate from pelvis and lower extremities. Iliac muscles are comprised of psoas, iliacus and quadratus lumborum muscles.

Psoas major muscle originates from vertebral bodies of T12-L5 and both their discs and transverse processes then ends at minor trochanter of femur. Iliacus muscle originates from upper part of iliac fossa and also ends at minor trochanter of femur just after merging with psoas major (Middleditch and Oliver, 1991). In anatomy, the combined form of these two muscles is referred to iliopsoas muscle and their main function is defined as hip flexion. However, if femur is fixed the contraction of ilipsoas muscles bilaterally bends the body forward and tilts the pelvis anteriorly. Studies also indicated that ilipsoas muscles are still active during sitting to stabilize the trunk. Due to their origins on vertebral discs and bodies bilateral contraction of iliopsoas muscles increase anterior displacement and compression forces on the lumbar spine (Bogduk et al., 1992). This can be easily explained with the need of individuals with back pain flexing their knees and hips to relieve the pain. This relief is gained by decreasing the stretch on iliopsoas muscle accompanied by reduced compression forces on the lumbar spine caused by taut iliopsoas (Sahrmann, 2002).

Psoas minor is one of the muscles that may or may not be present in human body. Approximately 40% of individuals do not have this muscle. Studies indicate that this muscle works during forward bending as a weak trunk flexor (Middleditch and Oliver, 1991).

Quadratus lumborum muscle attaches to 12th costae and transverse processes of L1-L4 and posterior part of iliac crest (Middleditch and Oliver, 1991). Unilaterally and on a fixed pelvis this muscle laterally flexes the trunk. On the other hand, the opposite quadrates lumborum also helps aforementioned lateral bending movement by contracting eccentrically thus controlling the motion (Sahrmann, 2002). Bilaterally contracted, they perform extension movement. Also they depress their origins on 12th costae bilaterally to help inspiration and stabilize one of the attachments of diaphragm. Studies indicate that aforementioned old anatomical functions of quadratus lumborum may not be true. As more recent literature showed that the force exertion rates of erector spina and quadratus lumborum are not quite the same. Main extensors of trunk – erector spina – creates 100 Nm and multifidi 150 Nm of force whereas quadratus lumborum creates about 10 Nm. Due to these results it was considered that quadratus lumborum, most likely, is not able to extend trunk the in the sagittal plane. Researchers also found that the same principle is also valid for lateral flexion. They concluded that main feature of quadratus lumborum is its important location in body. By the help of this important location quadratus lumborum forms a point of intersection of forces created by other muscles. This theory also explains the reason why this muscle contains chaotic fiber alignment. With these two features (important location and chaotic fiber alignment) the effect or exerted force of other muscles can be dampened or amplified.

Anterior abdominal muscles are comprised of external/internal oblique abdominal muscles, rectus and transversus abdominis. Even though these muscles do not have direct attachments to spine, their effects are undeniable. Anterior abdominal muscles take part in movements of the spine in three planes; forward flexion and lateral flexion, and rotation. Additionally their activity may change intra abdominal pressure and also help maintain posture. Abdominal muscles maintain balance by stabilizing the trunk and spine during active extremity movements. In order to perform activities with extremities, arm and leg muscles requires a fixed base so that they could contract optimally. Besides, disrupting effect of extremities on balance (stable state) is compensated and minimized with the help of maneuvers that are performed at trunk (Sahrmann, 2002).

Studies indicated that one of the main functions of abdominal muscles during activities of daily living is to control rotational movements of the trunk with isometric contractions. It was also mentioned that in some cases, low back pain, may be caused due to the lack of rotational control of the spine which increase shear forces. On the other hand, over active or stiff anterior abdominal muscles alter the alignment of the spine even though they do not attach the spine directly. In this example stiff abdominal muscles create a force vector, which decreases lumbar lordosis by tilting the pelvis posteriorly (Brown et al., 2011).

External oblique abdominal muscles attach to last eight costae and iliac crest. As the widest of all abdominal muscles when contracted bilaterally they flex the body forward and tilt pelvis posteriorly so that the anterior shear forces created by hip flexors could be neutralized. Unilaterally it contracts with contralateral internal oblique muscle to rotate trunk: to rotate left, internal oblique of the left side and external oblique of the right side contracts. Another important feature of external oblique muscles is that they depress the lower costae to help expiration by pushing diaphragm upwards (Cramer et al., 2014).

Internal oblique muscles have attachments on thoracolumbar fascia, linea alba and last four costae (Cramer et al., 2014). In addition to their function during rotation of spine mentioned above, unilaterally, internal oblique muscles contract with their ipsilateral external oblique muscle to perform lateral flexion of the trunk (Kendall et al., 1973).

Rectus abdominis muscle lies along the abdominal wall and attaches to xiphoid process, costal cartilages of 5th to 7th, pubic crest and symphysis pubis. This muscle is covered by the aponeurosis of oblique and transverse abdominal muscles. Rectus abdominis flexes lumbar spine and bends the trunk forward on fixed pelvis. If the fixed segment is trunk it tilts the pelvis posteriorly (Brown et al., 2011). In addition it forms a base for other abdominal muscles to attach to (Cramer et al., 2014).

Transversus abdominis muscle is located beneath internal oblique muscles and has attachments on thoracolumbar fascia, iliac crest, inguinal ligament, costal cartilage of the last 6 costae. Most fibers of transversus abdominis aligns horizontally and forms an aponeurosis. As in anterior view it is quite similar to a belt that covers anterior abdomen. When contracted transversus abdominis straightens abdominal wall and tidies up internal organs. It also attaches to transverse processes of vertebrae via thoracolumbar fascia thus helps stabilization of spine. Studies indicate that contraction of transversus abdominis also increases the stiffness in sacroiliac joint that's why during sacroiliac joint dysfunctions role of this muscle should be considered accordingly.

Studies including transversus abdominis muscle found that this muscle is the very first one to contract in means of providing postural stability during extremity movements in standing posture (Cresswell et al., 1994; Hodges and Richardson, 1997). It was concluded that the disruption of its function or a delay of contraction that alters the order of contraction may lead to low back pain (Allison and Morris, 2008; Allison et al., 2008; Vasseljen et al., 2012).

Lower extremity muscles which have attachment(s) on pelvis functionally may affect spinal movements by tilting the pelvis. Studies indicated that when normal alignment and balance of the pelvis is disrupted, whole body alignment may alter. Alteration in pelvic position also relocates muscle origins and insertions on itself leading to postural control problems, muscle spasms, decreased muscle strength etc. (Middleditch and Oliver, 1991).

Hamstring muscles mainly extends hip or flexes knee and tilts pelvis posteriorly. Due to their effect on pelvis, hamstring muscles may increase flexion of the lumbar segments. Over flexion of the lumbar area is a commonly seen condition that occurs to compensate posterior tilting of the pelvis which may be caused by stiff hamstring muscles. Eventually anterior shear forces are amplified and the mobility of the spine increases abnormally. Such compensation may occur during activities of daily living since the individual needs to take his/her shoes from ground, pick the coin he/she dropped and so on. The mechanism behind this condition is quite simple and can be explained by the increase in stiffness of the hamstring muscles reducing the anterior rolling of pelvis on femur in means of range. This leads lumbar region to compensate for the limited motion by increasing coupled movement of vertebral segments thus getting close to anatomical borders in order to achieve the task. Prolonged compensation disrupts the balance between hip and lumbar flexion during forward bending and results in postural malalignment and low back pain (Jandre Reis and Macedo, 2015).

Gluteus maximus muscle arguably is the greatest muscle in human body. Also this muscle is considered to be one of the muscles that contribute to sustaining erect posture. Gluteus maximus attaches to sacrum, coccyx, sacrotuberous ligament, aponeurosis of erector spinae, iliotibial tractus and femur. When contracted it extends hip, however it was mentioned that upper fibers of gluteus maximus are also activated during abduction. If the femur is fixed with the help of hamstring muscles it performs posterior tilt of pelvis (Cramer et al., 2014).

Instantaneous axis of rotation

Instantaneous axis of rotation was first described in lumbar spinal segments by Haher (Haher et al., 1991). It can be defined as the theoretically static point in the disc during motion. Instantaneous axis of rotation is believed to locate at the posterior part of intervertebral disc space and very close to the intervertebral foramina (Fig. 17.2). The center of this axis may be changed during motion. Aiyangar et al, studied this hypothetic centers of path in healthy subjects during weight lifting (Aiyangar et al., 2017). They found that the centers of motion of the segments are displaced anteriorly during weight lifting. This displacement is greater at L2-3 level and smaller at L5-S1 level. It is clear that the center of rotation is not a fix point at all levels of the lumbar spine. Wattanannon et al studied the center and the pathway of instantaneous axis of rotation in patients with low back pain (Wattananon et al., 2018). They demonstrated less displacement and variability in individuals with low back pain potentially indicating different coping strategies to stiffen the lumbar spine during forward bending. Individuals with low back pain may have increased muscle activation. They also reported that when the individuals recovered from an episode of low back pain the instantaneous center of rotation of the movement was comparable to that of healthy participants without a history of individuals.

Lumbar vertebral column in pathological conditions

Disc herniation and degenerative spinal disease are two most common problems of lumbar spine in adults. Disc herniation generally occurs at degenerated discs. Intervertebral disc is avascular after toddler's period and disc cells feed via osmosis from vertebral end-plates. Disc cells diminish with advancing age and water content is reduced. Disc material dries, end-plates get closer and facet joints' capsules become thinner. In the long term, facet joint instability may occur. Secondary changes resulted from this instability are facet joint hypertrophy, marginal osteophytes at the edge of the end-plates, intervertebral foraminal narrowing and spinal canal stenosis. Degenerative changes such as Schmorl's nodes, degeneration or disruption of intervertebral disc and disc prolapse are closely associated with low back pain (Siivola et al., 2002; Videman et al., 2003). Symptoms may alter from individual to individual but low back pain generally is the major symptom. Schmid et al., studied lumbar spinal kinematic features in different age groups (Schmid et al., 2017). They found that lumbar lordosis increases during adolescence, reaches its peak during adulthood and then again decreases with advancing age although the latter is likely to be dependent on the highly variable effects of aging. The thoracic kyphosis also follows a similar pattern from adolescence to adulthood, but it increases with advancing age.

Global range of motion of lumbar spine and segmental movement are restricted in patients with low back pain. Christe et al., compared upper, lower lumbar and upper thoracic spinal kinematics in individuals with chronic low back pain and healthy subjects during sitting and standing (Christe et al., 2016). They found significant differences in sagittal plane angle and smaller angular velocity in individuals with chronic low back pain compared to control group at three different regions. This may imply that individuals with low back pain may have more rigid spine. They advocated that proper low back pain rehabilitation should be performed in individuals with low back pain including a prior analyses of spinal kinematics using a pelvis-lumbar-thoracic model including lower and upper lumbar and thoracic segments. In individuals with low back pain, restriction of motions may be a contributing factor to the path of progression that lead to chronic conditions. Hernandez et al., designed a study to compare the kinematic properties of lumbar spine, pelvis and lower extremities in individuals with low back pain and healthy controls (Hernandez et al., 2017). They found less lumbar spinal movement range than controls in all three planes of movement. This difference was most remarkable in the sagittal plane for lumbar spine; however, subjects with low back pain displayed more frontal and axial plane knee movement than controls in their lower extremities. This may indicate that individuals with low back pain may try to compensate their restricted lumbar motions by increasing their lower extremity mobility.

Lumbar disc herniation (LDH) can alter the lumbar spine kinematics in two ways. Firstly, it creates low back pain and restricts lumbar motions. Secondly, radicular compressions of prolapsed disc produce muscle spasms. Spasmatic paraspinal muscles and psoas muscle may lead to motion restriction and rigid spine but generally, this stiffness will be resolved with treatment. In prolonged situations, this muscle spasm can lead to chronic changes in muscle fibers and permanent disruption of spinal kinematics. Kuai et al., compared spinal kinematics in the individuals with protruded disc fragment and healthy subjects during five activities of daily living (Kuai et al., 2017). They found that the individuals with lumbar disc herniation mainly restrict the motion of lower and upper lumbar spine during five components of daily living. In this situation, the patient needs to find a compensatory mechanism to perform their daily basic activities. Pelvic rotation is an important and compensatory mechanism. Increased pelvic tilt and hip-knee flexion may be helpful strategies in order to accomplish basic daily activities. For this reason, in this condition it is important to assess spinal kinematics and spinal motions. Motions should be examined in three planes during physical examination however, kinematic studies are still unavailable in most centers.

There are other studies comparing the firing ratio of spinal muscles to identify the importance of co-contractions and muscle recruitment patterns during spinal movements. Du et al., compared lumbar muscles co-contraction ratios in both people with LDH and healthy control group. The results indicated that individuals with LDH tend to use antagonistic muscles more as co-contraction ratios (EMG values of antagonist muscle/sum of EMG values of both agonist and antagonist muscles) were higher in individuals with LDH during trunk flexion, extension and lateral flexion. These results approved that stability of lumbar region may also be related to unusual muscle co-contraction ratios. Du et al., also hypothesized that antagonistic muscle activation increases to stabilize increased trunk moments thus creating higher loads on spine. However, they did not identify which one of the high co-contraction muscles or high spine loads in people with LDH is the result of another (Du et al., 2018).

Spinal instability is present in some spinal disorders such as trauma, degenerative spine, and destructive disorders or in iatrogenic origin. Spinal stability can be achieved with the use of implantation systems. Main goal in instability treatment is solid bony fusion. Spinal instrumentation and autogenous bone graft applications generally lead to solid fusion but this solid fusion carries some problems in long term follow-ups. There are six-motion segment between T12 and S1 vertebrae. They contribute to the motion of lumbar spine in different role. L4-L5 and L5-S1 motion segment is primarily responsible to resist to the shearing forces. That's why fusion of lumbosacral junction may lead to transfer of the shearing forces to the upper parts of lumbar spine.

Increased shear forces concentrates at the isthmus of a vertebra and fatigue failure may be seen at isthmus. Spondylolysis or spondylolisthesis may be developed. Spondylolysis may be defined as a condition that is a result of an anatomical defect or a fracture in pars articularis of vertebrae. Spondylolysis is mostly seen in L5-S1 junction followed by L4-L5 segment. Researchers claimed that this is mostly due to sacrohorizontal angle, which can be described as the angle between top of the sacrum and the transvers plane. This angle increases the tendency of L5 to shift anteriorly. To describe the effect simply an example may be given: continuous flexion posture during sitting or simply carrying a backpack most of the time may cause enough shear stress for pars articularis to deform and/or microfracture. Then the cycle feeds on itself to put more stress and eventually tore this bridge between two vertebrae apart. If complete fracture of pars articularis is present bilaterally there will be no structure to prevent the translation of the vertebra forward. This forward translation of vertebra is called spondylolisthesis. Anteriorly shifted vertebra may cause nerve roots to be compressed and cause additional symptoms of pain

(Gagnet et al., 2018). There other factors that may affect sacrohorizontal angle such as psoas muscles. Psoas muscles have the ability to translate forward and compress lumbar vertebrae. These muscles originate from transvers processes of lumbar vertebrae thus, allowing a lever arm that pulls vertebrae forward. Considering the normal lordosis in lumbar region, even though muscles originate from the same structures, their translation effect on each vertebrae varies. Normally lordotic pull of psoas muscles are neutralized by the opposite torque of rectus abdominis muscle. So, in presence of strong or spasmatic psoas muscles and/or weak rectus abdominis muscle the impact of forward translation increase exponentially and create more shear force. This brief example indicates that a simple muscle imbalance or weakness may also lead to spondylolysis and spondylolisthesis. That's why it is advised to evaluate psoas muscles and rectus abdominis muscle in case of spondylolysis spondylolisthesis

Another problem in long term follow-ups is the adjacent segment degeneration. Fusion of lumbar spine increases the axial and flexion-extension forces at the junction of fused and mobile segments. In active patients, hypermobility is seen at this motion segment. Disc is the first element of the spine which gives a reaction to this hypermobility and slow but astute degeneration may be developed in time. This degeneration may be symptomatic in some patients. But most of the patients are asymptomatic and exact cause is unknown. Sagittal alignment is very important when performing a surgery to fuse the spine in lumbar region. Hypolordotic or kyphotic instrumentation of lumbar spine increases the risk of symptomatic adjacent segment degeneration. Yet it is proved that such degeneration of lumbar spine, especially in apophyseal joints may also occur during childhood. Experts describe this phenomenon natural variations or developmental problems. According to studies the developmental problems of lumbar apophyseal joints may be related to their slow process of gaining normal alignment. Alignment of apophyseal joints of lumbar vertebrae takes too much time. Although it was reported that such asymmetry is present in most people, the problematic ones are also numerous. These asymmetric apophyseal joints may cause asymmetrical loads over vertebra leading to other problems mentioned above such as; spondylolysis and spondylolisthesis.

Sacroiliac joint dysfunction is a common entity in daily clinical practice. It has been ignored previously and frequently misdiagnosed as low back pain or back pain related to disc pathologies. Sacroiliac joint dysfunction is common in obese females. Multiple pregnancies are an important risk factor. Patients commonly suffer from back pain during walking and standing still. Rotation of pelvis or lumbar part of spinal column may provoke the pain. Special tests such as Gaenslen's test, Fabere or sacroiliac joint compression or distraction tests are helpful to differential diagnosis. There is no specific radiographic examination to diagnose the sacroiliac joint dysfunction. The diagnosis is identified by clinical evaluation and careful physical examination. Sacroiliac dysfunction is a motion based clinical problem and the condition of spinal and pelvic muscles may be the important factor. Clinical importance of motion restriction or motion preservation is still unknown in this clinical diagnosis.

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Chapter 18

Kinesiology of the pelvis

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Introduction

The pelvis of human had changed with the onset of bipedalism before 4–6 million years ago. These changes were necessary to gain access to habitual bipedalism by humans. Although there are some sex-specific variations, changes in the muscles also occurred as a result of changes in the bone (Lewis et al., 2017).

The pelvis of human plays an important role in many critical biological processes. The pelvis is a complex structure and important bone in human body in terms of locomotion, and obstetrics. It takes an important role especially in terms of obstetrics for providing bony support at birth (DeSilva and Rosenberg, 2017). It protects sensitive organs in the pelvic viscera and provide a stable point of attachment to the muscles (4). In addition, it plays an important role in maintaining balance through its functional relation with the axial skeleton. It also transfers body weight from axial skeleton to lower extremities via the pelvic girdle while standing (Fig. 18.1), or to the ischial tuberosities while sitting (Palastanga et al., 2006). Functionally pelvis consists of the sacrum, the coccyx, and two hemipelvic bones that has three parts: ilium, ischium and pubis (Fig. 18.2). There are three articulations which are sacrococcygeal symphysis at the inferior, sacroiliac (SI) joint at the posterior, and symphysis pubis in the anterior. As the pelvic ring forms a closed chain, any movement around the ring causes movement spreading through the chain (White et al., 2011). The pelvic inlet has an angle of about 60° with the horizontal plane.

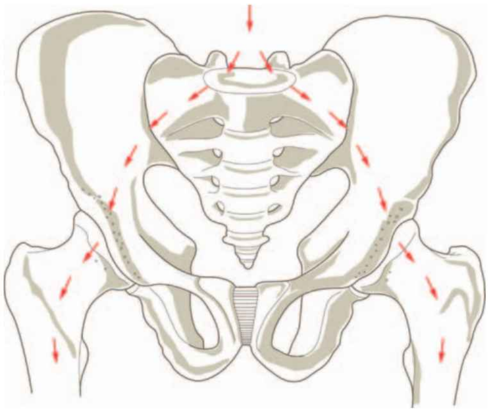

FIGURE 18.1 Transfer the body weight from the skeleton (Palastanga et al., 2006).

Another important task of the pelvis is to produce resistance to internal pressure. Many muscles and bundles of connective tissue fill the lower opening of the pelvis. They provide elasticity and tension between the pubic bone and the lower part of the spinal column much like as a hammock. This supporting elastic layer is called pelvic floor. While muscles provide an active support, connective tissues and fascia surrounding the pelvic floor introduces passive forces for stability. Muscles have important tasks in the pelvic floor (Fig. 18.3). They support the bladder and urethra within the pelvis and during activities such as coughing or lifting heavy objects. During such activities intra-pelvic/abdominal pressure increases and pelvis floor muscles support the bladder and urethra with their contraction. In this way they provide a subtle control over urination and defecation. When there is a suitable condition, the muscles relax completely, allowing easy urination and defecation (Eickmeyer, 2017).

When physiotherapists prescribe rehabilitation programs for individuals with hip trauma or related pathologies, they need to have sufficient knowledge about hip and pelvis anatomy and kinesiology as well as regional fundamental ligaments, muscles and their combined actions.

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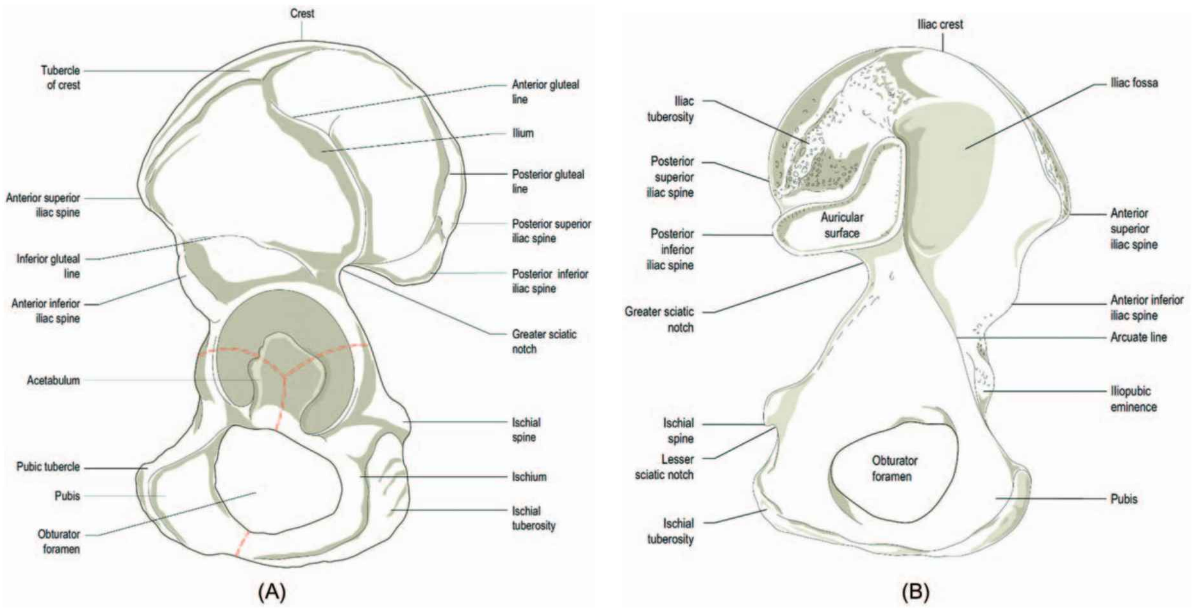

FIGURE 18.2 Parts of pelvic bone, lateral (A) and medial (B) views (Palastanga et al., 2006).

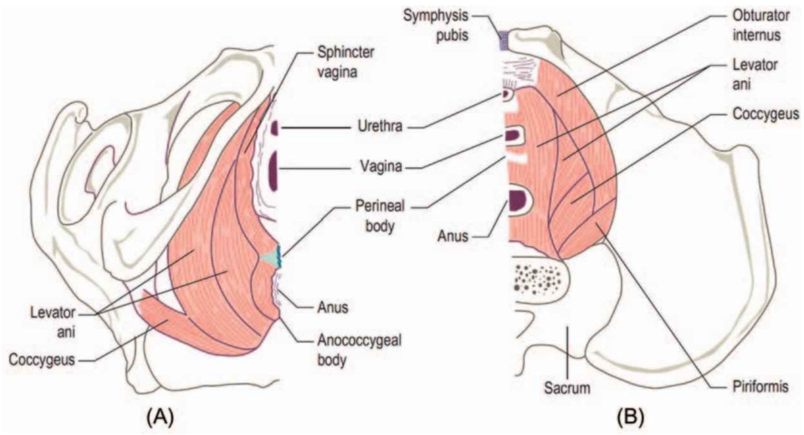

FIGURE 18.3 The pelvic floor muscles of female and neighbors: (A) inferior and (B) superior views (Palastanga et al., 2006).

Bones of the pelvis

The pelvis has two innominate bones each consists of the ilium, the ischium, and the pubis. These two bones articulate with the sacrum posteriorly and with each other anteriorly.

Ilium

It has two parts: corpus ossis ilii and ala ossis ilii. Corpus ossis ilii forms the upper part of the acetabulum and combines it with the other bones. Ala ossis ilii is the flattened part and is located above the corpus ossis ilii and expands upwards. The ala ossis ilii has three surfaces: glutaeal, iliac and sacropelvic

Pubis

Its sections include corpus ossis pubis, ramus superior ossis pubis and ramus inferior ossis pubis. Pubic bones coming from the right and left sides of the body approach each other at the midline and form symphysis pubis, which is a syndesmosis. The ramus superior extends laterally and forms one-fifth of the acetabulum

Ischium

It contains two parts: corpus ossis ischii and ramus ossis ischii. The body of the ischium is found in the lower part of the acetabulum and continues downwards to form ischial tuberosity, which is the insertion site of the hamstring muscles

Acetabulum

The hip joint is a classic ball-and-socket type of joint between the head of femur and the acetabulum. It possesses all four features of synovial joints: it has a joint cavity, joint surfaces covered by cartilage, a membrane producing synovial fluid and is preserved with a ligament-supported capsule (Kuran, 1983). The round, deep pit on the medial and external sides of the pelvic bone is called acetabulum. This pit forming the concave joint surface of the hip joint is formed by os ilium, os ischium and os pubis. The bodies of the ilium, ischium and pubic bone are joined by Y-shaped triradiate cartilage and ossificate at approximately 14–16 years of age to form the acetabulum. The edge of the acetabulum is called limbus acetabuli. The deep notch under this edge, which is not fully ring-shaped, is called incisura acetabuli. Behind it lies the ilioischiadic notch, whereas in the front lies the ischiopubic notch. The incisura acetabuli continues upwards with fossa acetabuli, which does not contain any joint surface. Between the fossa acetabuli and limbus acetabuli lies the crescent-shaped facies lunata, which is 2-cm wide, covered by hyaline cartilage and is the part that comes into contact with the femoral head. It is also the thickest part of the acetabulum (Schilders et al., 2011).

The acetabulum forms the hip joint by joining with the femoral head and has articular cartilage shaped as a horseshoe. The acetabulum rotates approximately 20°–40° off vertically in the frontal plane (Werner et al., 2012), and 20°–30° anteriorly (Fig. 18.4) (Werner et al., 2012), and 20°–30° anteriorly (Fig. 18.4) (Merle et al., 2013). The stability of the hip joint is provided by this position of the acetabulum in medial, superior, and posterior directions. The upper edge is the most circular part of the acetabulum. However, the depth of this structure only covers 170° of the convex shaped femoral head. Acetabular labrum increases the depth of the acetabulum. The labrum is a fibrocartilage structure made up of collagen fibrils that circumferentially adhere to the acetabular edge. It infero-laterally continues with the transverse acetabular ligament, which crosses the acetabular notch and becomes thinner at the superior of the acetabulum towards the load-bearing surface (Schilders et al., 2011). In their histological study, Seldes et al., reported that the labrum was joined to the acetabular cartilage with a 1–2 mm transitional zone (Seldes et al., 2001). Blood is supplied to the labrum via a vascular cascade of superior and inferior glutaeal arteries as well as an obturator artery, which penetrates labrum peripherally and crosses the surrounding cavity, as in the acetabular bone (White et al., 2011). The labrum is innervated by branches of the nerve to the quadratus femoris muscle and sensory branches of the obturator nerve. Demyelinated nerve endings are more remarkable in the superficial layer. Nociceptors and mechanoreceptors are also existing in the labrum (Kim and Azuma, 1995). The medial part, called acetabular fossa, does not have articular cartilage. Its bone structure is thin and it does not take part in articulation; further, it is covered with fat tissue and serves as an insertion site for ligamentum teres. The acetabular socket inferiorly terminates with the transverse ligament, which then turns this notch into a hole by attaching to the edges of the acetabular canal. Vessels and nerves coming to the joint pass through this point.

Center-edge angle, which defines the amount of coverage of the femoral head by the acetabulum, is important to determine the risk of acetabular dislocation. If center-edge angle decreases, the risk of dislocation increases. This angle is measured with radiography, and its mean value is 35° in adults (Bizzini et al., 2007; Genda et al., 2001). If center-edge angle reduces to 15°, the normal contact area decreases by 35%. Following that, the pressure increases by 50% on the joint surfaces. As a result, acetabular labrum degeneration and hip osteoarthritis may be seen too early (Neumann, 2010a,b).

Pelvis-related joints

Pelvis-related joints are in posterior, anterior, and inferior directions. Posteriorly, the sacrum forms two joints with

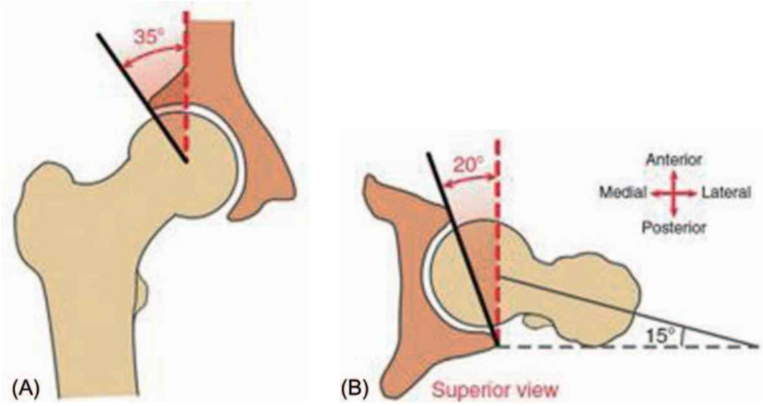

FIGURE 18.4 Acetabular angle, vertically (A) and anteriorly (B) (Neumann, 2010a,b).

both iliums, and they are called sacroiliac joints (SIJ). In the anterior, the pubic bones form the syndesmotic joint namely as symphysis pubis. Inferiorly, femoral head forms the hip joint with acetabulum, and in posterosuperior, sacrum constitutes a joint with fifth lumbal vertebra.

Sacroiliac joint

The SIJ is on each side between sacrum and iliac bones of the pelvis. It transfers all stresses that come from the upper body or lower extremities. The sacroiliac joint, which is very strong and less mobile, is responsible of many functions. First, SIJ works like as the center of the body's shock absorption system. When shock is transferred to upper or lower direction, a motion occurs much like as a spring in the lower extremity. The feet pronate, the fibulaes moves inferiorly (Weinert et al., 1973), the knees flex while tibias rotate internally relative to the femurs. Iliac bones and sacrum rotate in opposite directions (i.e. when iliac bones rotate posteriorly, the sacrum rotates anteriorly). During this movement, the sacrum and ilium are closer (Solonen, 1957; Vleeming, 1997; Vukicevic et al., 1991). Second; the weight of the entire upper body builds on the sacrum. The weight is transferred from the sacrum through the SIJ to the innominate bones and legs. Third; the nutation/counternutation movements of the sacrum provides balance during weight distribution. When one side of the body is in nutation, the other is in counternutation. In nutation, posterior innominate movement blocks anterior sacral movement. In counternutation, posterior sacral movement blocks anterior innominate movement. In addition, axial rotation of the pelvis is countered by contralateral movements of sacral and spinal segments. Fourth; the SIJs serve as proprioceptive center which control and orient the body's posture through muscle activation or inhibition. Fifth; the SIJ allows sacrum to function as a center between the ilia (Levin, 1995). Forces related to walking are transferred from the legs, through the pelvic bones to the spine and cranium in a unilateral alternating fashion. Finally; mobility of the SIJ and the symphysis pubis allow separation of the pelvis during delivery.

The sacroiliac joint is surrounded by many ligaments. Strong ligaments – while wrapping, the auxiliary ligaments provide additional stability. The anterior sacroiliac ligaments consist of the anterior longitudinal ligament (Fig. 18.5A). With the sacrospinous ligament, it restricts upward movement of the sacrum and lateral movement of the ileum. The posterior sacroiliac ligaments consist of four parts (Fig. 18.5B). They are the short-long dorsal sacroiliac ligaments, the supraspinous ligament, the iliolumbar ligament, and the sacrotuberous ligament. Downward and upward movement of the sacrum and medial movement of the ilium is restricted by the posterior sacroiliac ligaments (Palastanga et al., 2006; Foley and Buschbacher, 2006; Cohen, 2005). They are shown in Table 18.1. All of ligaments stabilize the sacroiliac joint together. There are a lot of nociceptors and proprioceptors within the ligaments around the sacroiliac joints and hip joint. They can be affected by the strong forces that are transferred from these joints (Vleeming et al., 1996). Thus, for example, the long dorsal sacroiliac ligament may be an origin of posterior pelvic pain (Vleeming et al., 1996).

The symphysis pubis

Symphysis pubis is a cartilage joint between both pubic bones. It has irregularly and grooved two articular surfaces that are covered by a thin cartilage (Palastanga et al., 2006), Articulation fits snugly by irregular surfaces,

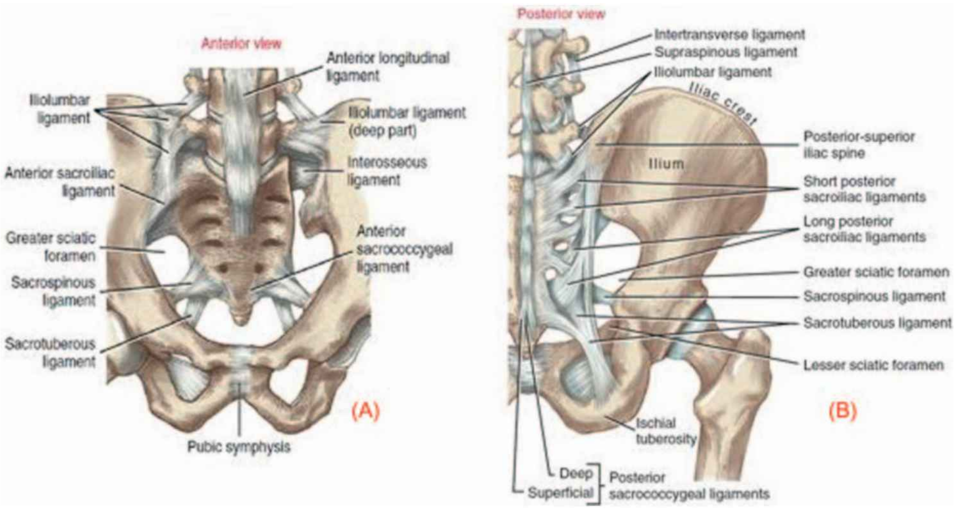

FIGURE 18.5 Anterior (A) and posterior (B) sacroiliac ligaments (Neumann, 2010a,b).

TABLE 18.1 Ligaments of sacroiliac joint.

Ligaments	Features
Anterior Sacroiliac Ligament	Strong and thick ligaments consisting of a large number of thin bands. It stretches from the ala and pelvic surface of the sacrum, above and below the pelvic brim, to the adjoining margin of the auricular surface of the ilium. the ligament is stronger in females.
Posterior Sacroiliac Ligaments	**Interosseus sacroiliac ligament**: this short, thick and very strong ligament is the ligament found most deeply among the posterior ligaments.
	Long and short posterior sacroiliac ligaments: The posterior ligament consists of numerous bands passing between the two bones. the short posterior sacroiliac ligament is found in the upper part of the cleft between the two bones passing horizontally between the first and second transverse tubercles of the sacrum and the iliac tubersity. the long posterior sacroiliac ligament has the longest and most superficial fibers of the posterior complex.
Accessory Ligaments	**Sacrotuberous ligament:** This ligament is a flat, triangular band of great strength. Superiorly it is attached to the posterior border of the ilium between the posterior inferior iliac spines, to the back and side of the sacrum below the auricular surface, and to the side of the upper part of the coccyx. From this extensive attachment the fibers pass downwards and laterally towards the ischial tuberosity, converging as they do so. the ligament as a whole is narrower in the middle than at either end.
	Sacrospinous ligament: The triangular sacrospinous ligament lies deep to the sacrotuberous ligament. Its broad base is attached to the edge of the lower sacral and upper coccygeal segments in front of the sacrotuberous ligament.

and there is a interpubic disc between articular surfaces that changes its size in relation with gender. As the pelvic ring creates a closed chain (Lewis et al., 2017), the symphysis pubic joint is reinforced with superior, inferior, anterior, and posterior ligaments. Their functions are to resist tension, shearing, and compression forces. These ligaments and the joint undergo enormous mechanical stress as result of widening during pregnancy (Eickmeyer, 2017). Estrogen, progesterone, and especially relaxin are hormones responsible of relaxation to decrease these forces (Snell, 1995).

The hip joint

This joint forms between the pelvis and the femoral head (White et al., 2011). It is a synovial joint and resembles a ball-and-socket relation. This joint moves in the all three planes (frontal, sagittal, and transverse). Joint stability is provided by the bony position (especially acetabular composition) and other structures which are: the acetabular labrum, ligaments, and joint capsule, and muscles. The acetabular labrum deepens the hip joint, and covers the articular surface (Hlavacek, 2002). The primary ligaments of the hip are named as iliofemoral, ischiofemoral, and pubofemoral which tighten especially in hip extension for stability. The joint capsule and ligaments are tightest in extension, mild internal rotation, and abduction (Neumann, 2010a,b).

The best fit of the hip join appears in 90° of hip flexion with middle abduction and external rotation. Although the ligamentum teres is smaller than other hip ligaments, it contributes the stability at the end of the range, especially in abduction and both rotations (Martin et al., 2013). It prevents subluxation of the femoral head during combination of flexion and abduction (Kivlan et al., 2013). In addition, this ligament supports vascularization of the femoral head.

Muscles of the hip are responsible for dynamic stability. There are two type of muscles. First group muscles such as the external rotators, iliopsoas, and gluteus medius and minimus are positioned near the axis of rotation in the joint. They mainly provide stability. Second group muscles are located far from the center of rotation, thereby, they provide joint torque (Retchford et al., 2013).

The lumbosacral joint

This joint is located between inferior surface of last lumbar vertebra and superior surface of sacrum. This joint consists of two bones, intervertebral disc, ligaments, and synovial joints. Iliolumbar ligaments, lateral lumbosacral ligaments, and intra/intervertebral ligaments together stabilize the lumbosacral joint (Fig. 18.6). This junction is very weak point in the vertebral column due to its inclination. Inclination angle is approximately 30° between superior of the sacrum and the horizontal plane. In addition there is nearly a 140° angle between the axis of fifth lumbar vertebra and the axis of the sacrum. This inclination angle causes a tendency of slippage between vertebrae. However, in the healthy, it is prevented by the

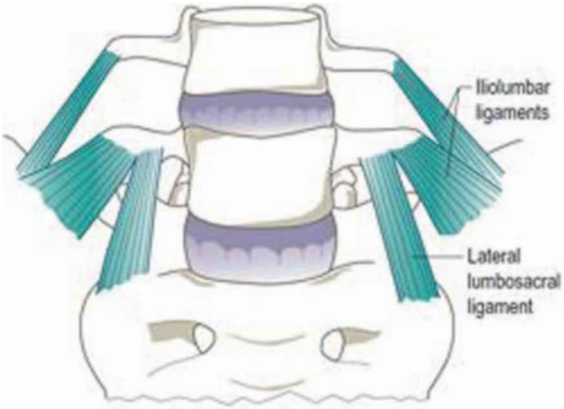

FIGURE 18.6 Lumbosacral joint with Iliolumbar ligaments, and lateral Lumbosacral ligaments (Palastanga et al., 2006).

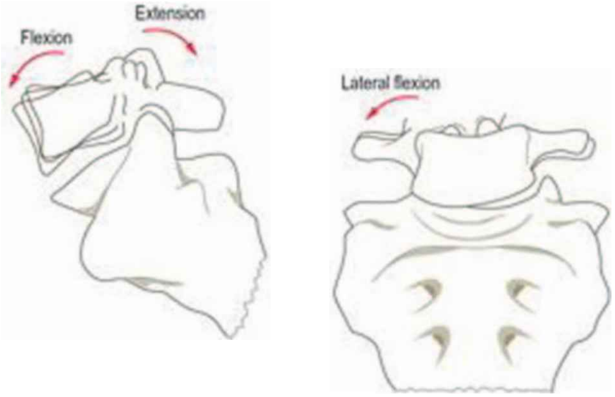

FIGURE 18.7 Movements of lumbosacral joint (Palastanga et al., 2006).

passive tension in the ligaments and the overlapping architectural features of the articular processes. As a result stability is maintained (Palastanga et al., 2006).

In this joint, although there are flexion, extension and side bending movements, rotation does not occur (Fig. 18.7). While nearly 75% of the total range of motion of flexion and extension movements occur at the lumbar region, the range decreases after 35 years old. Range of motion in flexion and extension are restricted by iliolumbar ligaments. Especially, extension is restricted by the inferior band, and flexion is restricted by the superior band of this ligament. Lateral flexion is nearly 7° during childhood. It reduces to 1° in the adults, and to 0° in the elderly. This movement is restricted by the contralateral iliolumbar ligament (Palastanga et al., 2006).

Motions of pelvis on the femur

The pelvis is an important bone in the human body in terms of locomotion (DeSilva and Rosenberg, 2017). It also provides a stable surface for the muscles originating. In addition, pelvis is a key bone for the maintenance of balance due to its relation with the axial skeleton. Another role of the pelvis is that, it transfer the body weight to lower extremities via the pelvic girdle while standing, or to the ischial tuberosities while sitting (Palastanga et al., 2006). Pelvis also moves in three planes for efficient gait (Lewis et al., 2017).

Movements in the sagittal plane

The rotation direction of an iliac crest determines pelvic tilt direction in the sagittal plane. During anterior pelvic tilt, hip flexion occurs and the rotation axis for the tilt goes through the femoral heads, and as a result the lumbar lordosis increases. The healthy adult can carry out an additional 30° of pelvic-on-femoral hip flexion in sitting position with the hips 90° flexion, and further movement is limited by lumbar spine extension restriction. The tension in the iliofemoral ligament and in most of the other hip ligaments decrease in full anterior pelvic tilt. If the hamstrings are tight, anterior pelvic tilt can be restricted by the hamstrings while the knee is held in extension (Neumann, 2010a,b). While standing with full knee extension, anterior pelvic tilt can be resisted by the elongated hamstrings. But this resistance is usually insignificant in the normal muscle (Li et al., 1996).

Posterior pelvic tilt enables the hips to be extended to 10°–20° at sitting position. This rotation movement increases length and tension of the iliofemoral ligament and rectus femoris muscles minimally. Flexion and flattening are seen in the lumbar spine during posterior pelvic tilt (Neumann, 2010a,b).

Movements in the frontal plane

During standing on one extremity, the iliac crest is raised on the other side with the support of the hip abductors. If the trunk is kept immobile, it is necessary for the lumbar spine to rotate in the opposite direction of pelvic movement, resulting in a lateral lumbar convexity ensues towards the abducting hip.

The natural limit of lumbar spine lateral bending is nearly 30°, and it is restricted by pelvic-on-femoral hip abduction. This movement can also be limited by tight hip adductor muscles and the pubofemoral ligament. Significant contracture in the hip adductor muscles may lead to landing of the non-support hip's iliac crest compared to that of the support hip and interferes with walking. Support hip adduction develops with nonsupport hip iliac crest landing, which also causes lumbar region lateral concavity on the adduction side. As a result, some motion may be limited due to hypomobility of the lumbar spine, and/or stiffness of the iliotibial band and/or abductor muscle (Neumann, 2010a,b).

Movements in the horizontal plane

Pelvic rotation on femur occurs around a longitudinal axis of rotation in the horizontal plane. While the support hip is rotating internally, the nonsupport hip rotates forward in the horizontal plane or vice versa. When the pelvis is rotating and the trunk is as far as fixed, the lumbar spine rotates in the opposite direction to the pelvis. However, the lumbar spine can normally move a little axial rotation and this movement limits full rotation of the support hip. Therefore, full movement requires both the lumbar spine and trunk to match pelvic rotation. This movement can be occurred with an ipsidirectional lumbopelvic rhythm (Neumann, 2010a,b).

Lumbopelvic rhythm

The sacroiliac joints have an important task of such as consolidating the axial skeleton's caudal end to the pelvis. During pelvic-on-femoral hip flexion, lumbar spine configuration changes. There are two opposite lumbopelvic rhythm in frontal and horizontal plane. They are the ipsidirectional lumbopelvic rhythm and the contradirectional lumbopelvic rhythm. During the ipsidirectional lumbopelvic rhythm, the pelvis and the lumbar spine rotate together with same direction, and trunk angular displacement is maximum. But during the contradirectional lumbopelvic rhythm, the lumbar spine and the pelvis rotate opposite direction, and body part above the first lumbar vertebra keep nearly static position, as in gait. The trunk must be fixed in walking whatever the pelvic rotation. In addition, the lumbar spine natural movement can restrict Pelvic-on-femoral rotation (Neumann, 2010a,b).

Movements of sacroiliac joint

The movement of the sacroiliac joints (SIJ) occur in multi-plane. At the same time, SIJ has rotational and translational movements along three axes between the left and right posterior superior iliac spines (PSIS) (Smidt et al., 1995). The transverse axis courses mediolateral through both PSIS, with corresponding sacral rotation in the sagittal plane. Around the longitudinal axis in the horizontal plane sacral rotation occurs. Finally, sacral rotation occurs around the sagittal axis in the coronal plane that occurs in the anterior-posterior direction between the anterior superior iliac spines (ASIS) (Sturesson et al., 1989).

According to Goode, reviewing the literature for quantity of movement of the sacroiliac joints in both in vivo and in vitro studies, rotation ratio is between −1.1° to 2.2° along the transverse axis, −0.8° to 4.0° along the longitudinal axis, and −0.05° to 8.0° along the sagittal axis. Translation ratio is between −0.3 to 8.0 millimeters (mm) along the transverse axis, −0.2 to 7.0 mm along the longitudinal axis, and −0.3 to 6.0 mm along the sagittal axis (Goode et al., 2008).

Pelvic motion during human gait

The pelvis moves in all three planes during walking, and these movements depend on the walking speed. Larger movements are seen during fast walking (Bejek et al., 2006). The pelvis is kept in anterior pelvic tilt during gait in the sagittal plane (O'Neill et al., 2015). Two cycles of sinusoidal waves are seen for each gait cycle. After first contact of the foot, posterior pelvic tilt is seen. This period is under 20% of the overall gait cycle. Following that anterior pelvic tilt occurs lasting till to the contralateral foot contacts the ground. This period is approximately at the 50% of the gait cycle. These cycles repeats itself during gait (Fig. 18.8). The movement of the pelvis is nearly 2°−5° in the sagittal plane (Bruening et al., 2015).

At first contact, anterior superior iliac spines are in the same line. After the first contact, the pelvis drops (at less than 20% of the gait) and then raises again. When the other side contacts, the pelvis comes to neutral position again. The total movement of the pelvis is nearly

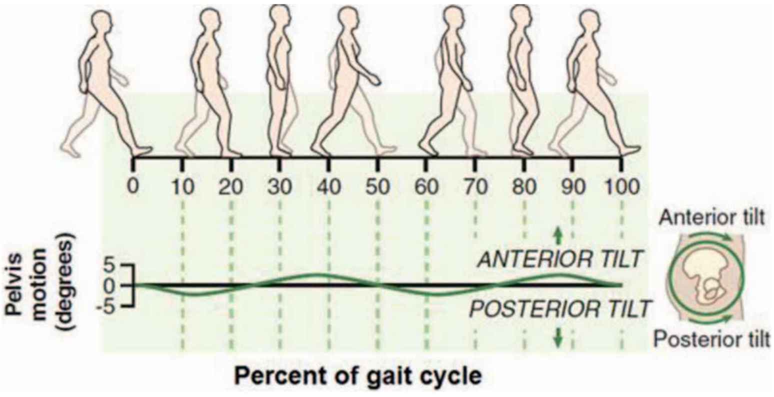

FIGURE 18.8 Pelvis motion in the sagittal plane during gait (Neumann, 2010a,b).

6°−11° in the frontal plane depending on walking speed (Dreyfuss et al., 2004).

During the first contact of the foot, anterior superior iliac spine at the opposite sides locate posteriorly in the transverse plane, and in the ipsilateral pelvis is positioned more anteriorly than the opposite side. The pelvis starts to move posterior direction just after ipsilateral heel strike, and then starts to move anterior direction when other foot is in heel strike. The size of the movement is between 3° and 14° in the transverse plane (Bruening et al., 2015), (Crosbie et al., 1997).

Femoral movements on the pelvis

Flexion and extension movements of the hip occur in the sagittal plane with rotation of the femur on the pelvis. The hip flexion is nearly 120° when the knee is flexed. The main capsular ligaments are relaxed when hip is in full flexion, but inferior capsule and muscles (gluteus maximus etc.) are stretched together. Hip's range of flexion is restricted 70°−80° when the knee is extended. This movement restriction is caused by the tension in the hamstring muscles. Hyperextension of the hip is approximately 20°. During full hyperextension, the iliofemoral ligament, other capsular ligaments, and flexor muscles' tension increase. If the knee is fully flexed, rectus femoris is also stretched and thus range of hip extension reduces (Neumann, 2010a,b).

Abduction and adduction movements of the hip occur in the frontal plane with rotation of the femur on the pelvis. Hip abduction and adduction are approximately 40° and 25°, respectively. Abduction is restricted by pubofemoral ligament and hip adductor muscles. Adduction is restricted by the hip abductor muscles, iliotibial band, and superior ischiofemoral ligament fibers.

External rotation and internal rotation movements of the hip occur in the horizontal plane with rotation of the femur on the pelvis. Hip internal and external rotation is approximately 35° and 45°, respectively. External rotation is restricted by lateral portion of the iliofemoral ligament, and the tension in the internal rotator muscles (Roach and Miles, 1991; Simoneau et al., 1998).

Pelvic pathomechanics in specific orthopedic conditions

The ligaments supporting the pelvic bones are the strongest ligaments in the body. The stabilization effects of these ligaments may be divided into two. Rotational stabilization forces arise from symphysis ligaments, sacrospinous ligament, anterior sacroiliac ligament and short posterior sacroiliac ligament. Meanwhile, vertical stabilization forces are produced by interosseous sacroiliac ligament, long posterior sacroiliac ligament, iliolumbar and lateral lumbosacral ligaments, and sacro-tuberous ligament (Tile, 1988; Star and Malekzadeh, 2010; Tang et al., 2002).

Pelvic fractures

Pelvic injuries are traumas that can be mortal and have high morbidity. Pelvic fractures are traumas that can be accompanied by head injury, urogenital and gastrointestinal organ injuries, bleeding and nerve damage acutely and in the latent period with severe pain, non-union fractures, leg length discrepancies and neurological sequelae in the late period (Tile, 1988; Star and Malekzadeh 2010).

The biomechanics of the pelvis or its fractures are not yet thoroughly understood because of its complex geometry and structural formation. The treatment of pelvic fractures is most often surgical and usually comprised of two main methods:

External fixation

Many of the external fixators are now considered as the gold standard in the acute approach to pelvic fractures. They can provide fracture stabilization and facilitate clot formation which help to shrink pelvic volume (Star and Malekzadeh, 2010).

Internal Fixation: It is reported that patients who had undergone internal fixation procedure have less pain and better surgical reduction (Matta and Tornetta, 1996).

Biomechanical studies related to pelvic fractures and surgeries are quiet scarce and they are usually comprised of experimental modeling or cadaver studies (Stewart et al., 2018; Futamura et al., 2018). It is understood that if the displacement of the SIJ is less than 1 cm, it causes a loss of vertical stability and also lateral displacement results in vertical instability (Ma et al., 2016).

In pelvic fractures, the pathologies and functionality of patients are often evaluated using Majeed Score. Gait speed and step length are significantly decrease after pelvic fractures treated with open reduction and internal fixation (ORIF) (Gruen et al., 1995). Kubota et al., using three dimensional movement analysis, assessed the gait of the patients with pelvic fractures treated with ORIF at 3 and 12 months following the surgery. They found that there was a decrease in the angle of hip abduction and extension after 3 months of surgery in stance phase. Moments of the hip abduction and ankle plantar flexion were decreased. Moments of hip abduction and ankle plantar flexion were normalized after 12 months, and the speed of gait and step length were better. Angle of hip adduction and moment of hip abduction decreased after 3 months of surgery. Moment of hip abduction is crucial for pelvic control, speed of gait and gluteal muscle strength. Authors suggested that patients developed a strategy to compensate the weakness of hip abduction strength. They reported that there were no changes in pelvic tilt, the patients' center of gravity shifted to the right side, and their step width increased. It was shown that there is 70% acquisition in the flexor, adductor, and abductor muscles of the hip after 3 months of surgery, and there is 90% acquisition at the 12th month (Kubota et al., 2013).

Rehabilitation program following surgery of pelvis fractures should include a regime enhancing control of the pelvic tilt and development of hip abduction. It may be suggested that patients should be followed at least a year.

Acetabular fractures

Acetabular fractures may occur due to in-vehicle collisions, falls from a height, and unexpected traumatic events around the hip and the pelvis. Acetabulum fractures are often treated with the surgical methods are used in which reconstruction plaques and fixators or screws using open anatomic reduction. During gait, sufficient muscle function is needed around the hip joint. Therefore, gait disorders are seen with muscle weakness after acetabular fracture surgery (Kubota et al., 2012; Dickinson et al., 1993). Kubota et al., showed the results of acetabulum fractures fixed with ORIF on the 3rd and the 12th months. It is shown that speed of gait, length of step and cadence decreased significantly after 3 months of surgery but all these parameters became close to normal value on the 12th month (Kubota et al., 2012). Authors emphasized that anterior pelvic tilt, hip flexion angle, and moments of hip abduction and extension decreased after 3 months of surgery. They suggested that abnormal pelvic tilt which is seen during gait may result from weakness/inadequacy of abdominal and spinal muscles.

It was shown that peak hip abduction moment that increases after 12 months of surgery decreased in 12th month. Although peak hip abduction moment did not change between the months 3–12, hip abductor muscle strength kept increasing during this period. That means increasing muscle strength does not affect peak hip abduction moment. These results point that gait pattern following acetabular fractures cannot be adjusted easily and it is impossible to get a solid result before a year. It may be suggested that rehabilitation programs following acetabulum fracture surgery should have a specific emphasis on improving peak hip abduction moment and patients should be followed at least a year (Kubota et al., 2012).

Acetabular dysplasia

Pelvic drop and forward displacement significantly increase during stance on the affected side with decreased transverse plane pelvic excursion in individuals with acetabular dysplasia (Romano et al., 1996). In addition, the hip extension movement decreases (Skalshoi et al., 2015). Individuals with femoroacetabular impingement syndrome (FAI) have a lower gait speed than normal, and they have lower hip extension, adduction and internal rotation (Hunt et al., 2013). However, these changes do not affect walking too much in FAI (Diamond et al., 2016).

Sacroiliac joint dysfunction (SIJD)

The SIJ is designed for stability. SIJ functions are transferring and dissipation of axial loads to the lower extremities, restricting axial rotation, and facilitating delivery. SIJ can withstand medially directed forces six times greater than the lumbar spine. But compared to the lumbar spine, it can withstand only half of the torsional and 1/20th of the axial compression loads (Dreyfuss et al., 2004).

SIJ dysfunction or sacroiliitis is described as the inflamation of one or two of sacroiliac joints. Osteoarthritis of SIJ, ankylosing spondylitis, gout, traffic accident or falling may result with injury to SIJ. The symptoms of SIJ dysfunction (SIJD) should be differentiated from sciatica, bulging disks, and arthritis of hip (Foley and Buschbacher, 2006), (Capobianco et al., 2018):

Inflammation and dysfunction accompanied by joint and muscle pain may cause a decrease in coordination and motor control. Load that is occurred with movement and transmitted from pelvis to SI joint is confronted by the surrounding soft tissues and the pain is felt. Individual restricts his/her movement and stay abstain from moving which may result in pain. This changes the load on lower extremity and ruin the gait pattern. All these processes may result in degenerative changes either in the spine and in the lower extremity as long as it is not treated (Foley and Buschbacher, 2006; Capobianco et al., 2018; Hodges and Smeets, 2015).

Posterior dysfunction is the most common lesion of the SIJ. If the anterior pelvis is not supported adequately, the pelvis rotates towards anterior and inferior direction. As a result, anterior dysfunction of the SIJ is seen (Vleeming et al., 1992).

Capobianco et al., showed that the erector spinae muscles were engaged sooner, the latissimus dorsi muscle was engaged later on the affected side, and the hip flexion angle was lesser in individuals with SIJD (Capobianco et al., 2018). Lattisimus dorsi provides stability to the SIJ especially during weight-bearing activities. Latissimus dorsi deficit is common during activities climbing up/down a ladder, sitting on a chair, and standing up from a chair.

Although sacroiliac joint movement is minimal, it is affected by loads from both the pelvis and the spinal column. It absorbs the load and transfers it. SIJ does not only affect nearby joints because it is an important central structure of the kinematic chain of the body.

Sturesson et al. (1989) evaluated SIJ movements in 25 patients diagnosed with SIJ pain. They found to be small movements with translations never exceeding 1.6 mm, and rotations limited to 3° in all planes. Vleeming et al. (1992) also defined that the total range of motion rarely exceeded 2° during flexion and extension at the SIJ, and being the upper limit 4° during axial rotation.

In the conservative treatment SIJD, underlying pathologies should be addressed. SIJ pain may occur as a result of altered gait mechanics and spinal malalignment. Physical therapy and/or manual therapy should be focused to reduce pain, to improve mobility, and to reduce axial rotation (Cohen, 2005).

Spondylolysis and spondylolisthesis in the lumbosacral joint

Spondylolysis is defect of pars interarticularis of vertebrae (Palastanga et al., 2006; Foreman et al., 2012). It is seen very often in L5 (71–95%), 80% bilaterally, and 4% on multiple levels (Bouras and Korovessis, 2015). Articular surfaces of sacrum and L5 normally fix tightly together. Thus stability is provided, and they can only move together (Palastanga et al., 2006). 75% of spondylolysis turns into spondylolisthesis (Bouras and Korovessis, 2015). Spondylolysis is usually seen at adolescents. It may have no symptoms. But neurological symptom can be encountered if spondylolisthesis exists (Foreman et al., 2012). Reduced lumbar lordosis, spasm, pain, tight hamstring muscles, and reduced step length may be encountered in spondylolysis. Pain increase with hyperextension, and decrease with rest (Foreman et al., 2012).

When one the body of lumbar vertebra, very often at L5-S1 (Fig. 18.9), moves towards anterior-inferior direction over sacrum, spondylolisthesis occures without any disruption or defect in the vertebral column (Snell, 1995), (Watters et al., 2009). Spondylolisthesis is seen in the elderly with degenerated spine (Watters et al., 2009), and in adolescents who perform contact sports or gymnastics (Palastanga et al., 2006). Following spondylolisthesis intervertebral disks try to maintain stability. Tension increases, pasm is seen in paravertebral muscles and pain that is associated with spondylolisthesis occurs. In addition, there may be muscle weakness, sensory deficits or cauda equina syndrome (Watters et al., 2009). However, there are no correlations between progression of clinical signs and progression of the slip (Matsunaga et al., 2000; Vogt et al., 1998).

Osteitis pubis

FIGURE 18.9 Spondylolisthesis at L5-S1 (Creative Commons Attributions 4.0 https://creativecommons.org/licenses/by/4.0).

Osteitis pubis is a noninfectious inflammatory condition of the symphysis pubis. It is usually seen in females after delivery, and in some football players. Although etiology is unknown, some reasons such as trauma, low-grade infection, abnormal stress, and venous congestion are thought to be the main reasons. The cause may also be multifactorial (Palastanga et al., 2006; Gomella and Mufarrij, 2017).

Pain may be seen at lower abdominal and suprapubic area or groin (Gomella and Mufarrij, 2017). A classic gait disturbance that is called "waddling" gait (a form of an antalgic gait) may also be present. "Pubic spring" test and "lateral compression" tests are specific physical examination tests that elicit pain. If pain is reproduced, the test is considered as positive (Hennion et al., 2010). The first treatment approach is conservative such as rest, usage of nonsteroidal oral anti-inflammatory drugs, and physical therapy. If conservative treatment fails, invasive surgical techniques may be thought (Gomella and Mufarrij, 2017).

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Part 5

Cardiorespiratory system

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Chapter 19

Kinesiology of respiration

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Introduction

The primary function of the respiration is the gas exchange that is essential to life. The exchange of oxygen and carbon dioxide occurs between the lungs and the blood. The muscle fibers, which move and stabilize the joints of body, use aerobic metabolism to convert chemical energy stored in adenosine triphosphate (ATP) into mechanical energy and the oxygen is an essential part of this process. In health, the respiratory system does not limit the exercise. In patients with lung disease, the loss of physiological reserve may limit even the essential activities of daily living.

The respiratory system is responsible for ventilation and the external respiration. The former means the movement of the air in and out of the lungs, and the latter is the gas exchange between the air in the alveoli and the pulmonary circulation. Ventilation consists of the mechanical process, which occurs with inhalation and exhalation through the lungs and airways. The ventilatory system is situated in the thorax and includes principle structures of airways, lungs, sternum, ribs, thoracic vertebra, respiratory muscles, and the central control.

Structure of thorax and lungs

The respiratory system has extra-thoracic and intra-thoracic components. One of the extra-thoracic components is the upper respiratory tract. The nose, pharynx, and larynx are the parts of the upper airways. The nose is responsible for warming, moistening, and filtering of the air. Nasal conchae are responsible for the regulation of airflow. The nasal conchae slows down the laminar flow, secured air spends a longer time in the cavity for humidification. Air moves through the nasopharynx and the larynx, and the trachea (Fig. 19.1).

The other extra-thoracic component of the respiratory system is the respiratory center that controls the respiration (McConnell, 2013; Jones et al., 2016). Central control is supplied by the respiratory control center, which is situated in pons and medulla oblongata. Its primary function is to deliver minute ventilation appropriate for the demands of the metabolism. The respiratory center receives inputs from the central and peripheral chemoreceptors. The former is located on the ventral surface of the medulla, and the latter is within carotid bodies and aortic arch. The chemoreceptors sense oxygen, carbon dioxide, and hydrogen ion contents in the blood (Fig. 19.2).

Conducting airways and the alveoli

Conducting airways are part of the lower respiratory tract, which does not directly participate in gas exchange. At conducting airways, trachea descends from the larynx into the thorax. Trachea and large airways have cartilages to prevent collapse during the pressure changes in the thorax. The trachea branches to the two main bronchi: right and left. Each primary bronchus divides and subdivides again into lobar bronchi, segmental bronchi, bronchi, and bronchioles. Terminal bronchioles are considered the final conducting segment and do not contain cartilages. Therefore, they are prone to bronchoconstriction during forced expiration. Since there is no gas exchange in the conducting airways, the volume of air in this section is often called anatomic dead space. Respiratory bronchioles include alveolar buds in their walls and end alveolar ducts where the gas exchange takes place. The smaller airways do not have supporting cartilages and are composed of smooth muscles when contracted, narrow the airways leading bronchoconstriction. Elastic forces of the surrounding parenchyma tug the airways open during expiration with their radial traction (McConnell, 2013).

The alveoli and surrounding capillaries ensure a surface for the exchange of oxygen and carbon dioxide through passive diffusion. There are some misconceptions should be clarified about the structure of alveoli, which

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have great importance and role in the mechanical properties of the lungs. Despite not being independent little balloons, alveolus with their terminal bronchiole has been likened to a bunch of grapes. Laplace's law, as applicable for spheres, was called as a mechanical model for the forces of alveolar inflation and used to explain why the pulmonary surfactant is required. However, the shapes of alveoli are prismatic or polygonal, and their walls are flat. Laplace's law in inflating applies to the minimal curved area in the fluid where these walls intersect, which means the law applies to cylinders is important for the airway collapse mechanics, but not appropriate to the individual alveolus (Prange, 2003). The anatomical interdependency of alveoli allows the stabilization of the alveoli during expiration and limits the tendency to collapse (Fig. 19.3).

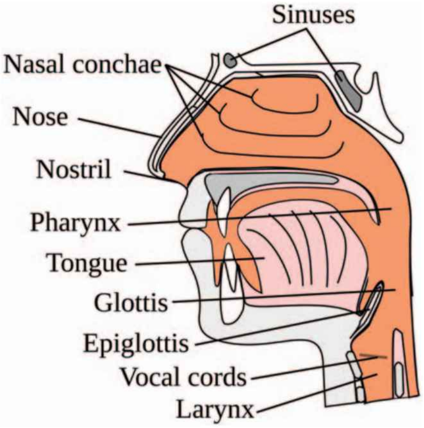

FIGURE 19.1 Upper airways.

The pressure in the alveoli is the combination of the lung elastic recoil pressure and the intrapleural pressure. The alveolar pressure is given according to the atmospheric pressure set to zero. The alveolar pressure determines whether the air enters the lungs. During inspiration, the air flows from the high pressure in the mouth to the low pressure in the alveoli when the alveolar pressure is negative. The positive alveolar pressure, during the expiration, enables the air flowing out. The alveolar pressure is equal to atmospheric pressure at the end of inspiration and expiration, and the flow temporarily stops.

Lungs

The lungs are located vertically around the heart within the thoracic cage. Their primary function is the gas exchange of oxygen and carbon dioxide between the alveoli and venous blood of the systemic circulation. The lungs occupy the lateral compartments of the thorax and exist within the pleural cavities. The right and left lungs have slightly distinct anatomies, mainly as a result of the heart's asymmetric orientation toward the left side of the thorax. The lungs are divided into independent compartments, lobes, and the right lung has three lobes while the left has two. The lobes of right lung are termed the superior, middle, and inferior lobes whereas the left lung only possesses a superior and inferior lobe. The left superior lobe has an anterior extension that curves around the anterior heart termed the lingula. The fissures separate the lobes of the lungs. The lungs are connected with the rest of the body at their "hilum" where airways, vasculature,

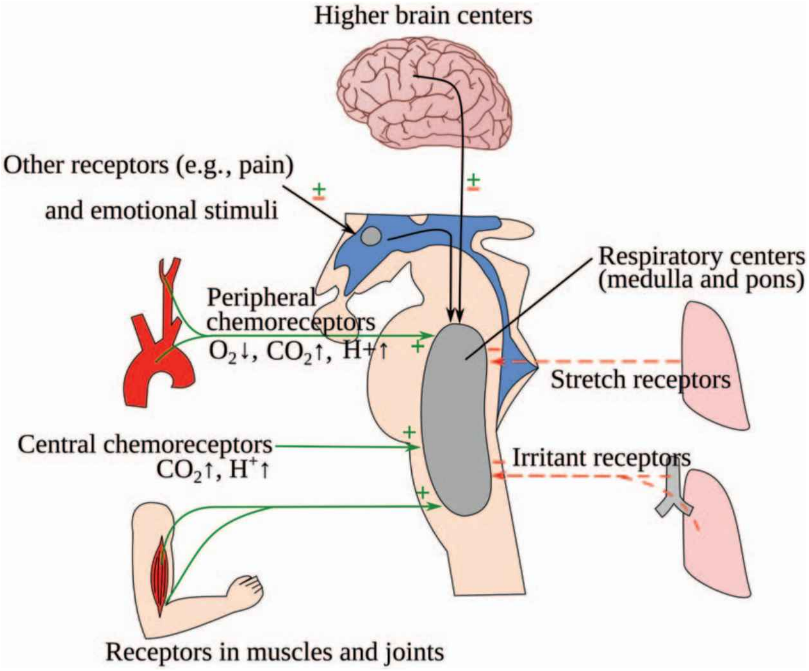

FIGURE 19.2 Control of respiration.

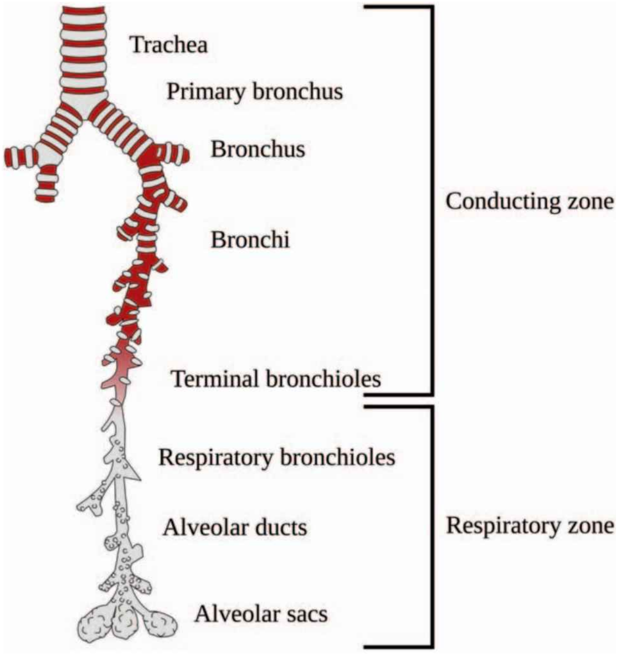

FIGURE 19.3 Conducting airways and the alveoli.

and nerves enter and exit the organs. The trachea divides into right and left main bronchi that serve their respective lungs. Here is also the location of the right and left pulmonary arteries, derived from the pulmonary trunk exiting the right heart. Each lung is perfused by pulmonary veins that in turn feed into the left atrium.

The lungs are surrounded by visceral pleura. A second layer, parietal pleura, covers the thoracic wall and thoracic surface of the diaphragm. The pleural fluid between the two layers of pleura allows gliding over each other during inspiration and expiration. The continuous negative pressure within the pleural space ensures a tight seal between the lung and the chest wall. Phrenic and intercostal nerves innervate the parietal pleura and so are sensitive to pain (Jones et al., 2016) (Fig. 19.4).

The complex interaction between lungs diaphragm and chest wall determine regional function. The resting volume of the lung is determined by the outward spring of the rib cage and the inward elastics recoil of the lung tissue. During inspiration lobar surfaces probably move relative to each other. The sliding and rotation motion reduce the lung parenchymal distortion and high local stress. Lungs are more expand at the diaphragm than at apex (Ding et al., 2009).

During ventilation, the air enters to the lungs based on the ideal gas law, which the pressure and the volume in the lungs is inversely related. Therefore, increase in lung volume leads decrease in pressure and a decrease in one result in increase in the other. Air flows from high pressure (atmospheric pressure) to areas of low pressure (intrathoracic pressure). When the intrathoracic pressure is high, air flows out of the lungs. The amount of air differs during ventilator cycle depending on the active and passive forces acting that alter the volume within the thorax. Total lung capacity is about 5 L of air. About 500 ml of air moves in and out of the lung, at rest, during each ventilatory cycle. This tidal volume increase of about 60% of vital capacity during exercise (Neumann, 2016) making ventilation is not a limiting factor in healthy individuals (Amann, 2012).

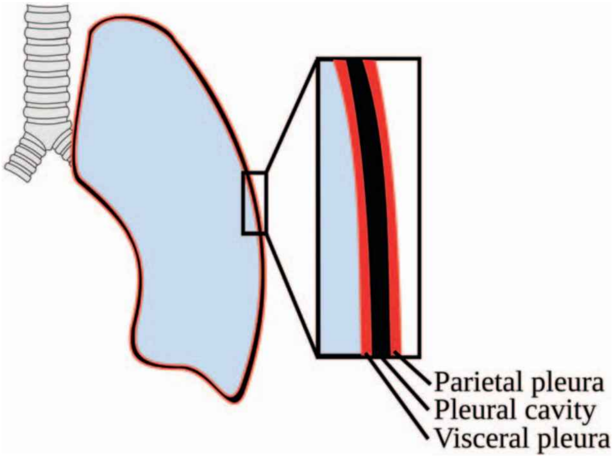

FIGURE 19.4 Pleural layers.

Thoracic cage

Thoracic cage, pleural space, and the patency of airways maintain the shape of the lungs. The contraction of the inspiratory muscles ensures the expansion of the lungs. The primary inspiratory muscles are diaphragm, scalene muscles and external intercostal muscles. Accessory muscles are responsible for deep inspiration and the forced expiration.

Thoracic cage consists of several structures including sternum, ribs, and thoracic vertebrae. The sternum includes manubrium, the body, and the xiphoid process. The thoracic spine has a kyphotic curve (i.e., it is concave anteriorly). The thoracic spine is far less mobile but more stable than the cervical and lumbar regions. The presence of the rib cage and long and inferiorly oriented spinous processes limit the movement of the thoracic spine (Muscolino, 2006; Sen Özipek et al., 2016).

A series of costal facets on the sternum articulates with the tubercle of the corresponding rib. There are 12 pairs of ribs. Ribs 1–7 are called true ribs, and they attach directly to the sternum by costal cartilages. The ribs 8–10 join the costal cartilage of rib 7. The ribs 11 and 12 do not attach to the sternum, and they are floating anteriorly (Fig. 19.5).

The ribs articulate with the thoracic vertebrae posteriorly. The head of the rib is wedge shape and has two articular facets to form costovertebral and costotransverse joints. The head of the rib articulates with the vertebral body at the corresponding level to form a costovertebral joint and stabilized by its fibrous joint capsule and the radiate ligament (Muscolino, 2006). Beyer et al. (2016) reported that the axes of rotation of the ribs are similar for each costovertebral joint, and lung volumes were not associated to costovertebral joint kinematics. While the range of motion decreases gradually from upper to lower costovertebral joint level, rib replacement was also found to be reduced if lung volumes above the middle of inspiratory capacity, and. The ribs and their motion with intercostal muscle activity also stabilize the thorax during inspiration (Wilson and De Troyer, 2004; De Troyer et al., 2005).

The costotransverse joint is where the tubercle of the rib articulates the adjacent transverse process of the thoracic vertebrae. The costotransverse joint is stabilized by four ligamentous structures: a fibrous joint capsule, a costotransverse ligament, a lateral costotransverse ligament, and a superior costotransverse ligament.

Both costovertebral and costotransverse joints are synovial, non-axial joints, and allow gliding motion. The joints stabilize the ribs by giving them a posterior attachment to the spine and allow mobility of the ribs relative to the spine (Fig. 19.6). Ligaments stabilize the both joints are normally not in a resting condition because they involve the movement of the thoracic cage during every respiratory effort (Saker et al., 2016).

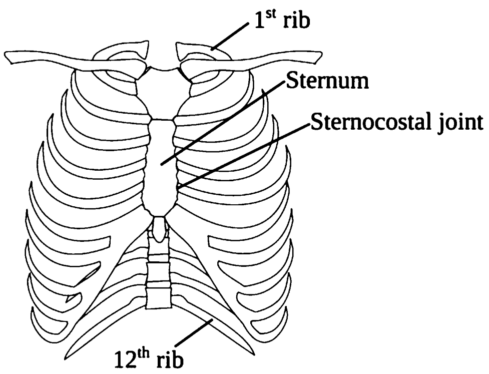

FIGURE 19.5 Anterior view of the thoracic cage.

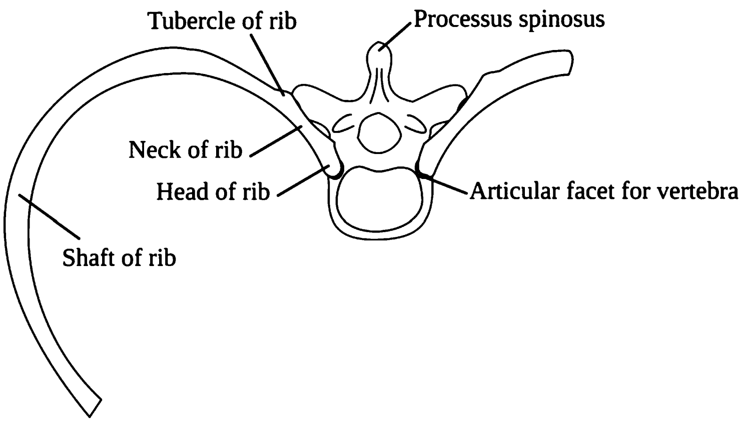

FIGURE 19.6 Joints between a rib and the spinal column.

The ribs are involved in both respiratory function and thoracic spine stability (Cappello and De Troyer, 2002). The proper movement of all rib joints is extremely important during respiration to increase and decrease the vertical, transverse, and anteroposterior dimensions of the thorax during inspiration and expiration, respectively. The sternum and the anterior ends of ribs 2–5 move during inspiration and increase the anteroposterior diameter of the thorax (pump handle movement). The anterior ends of the ribs 8–10 are raised upwards and outwards to increase the transverse diameter of the thoracic cage (bucket handle movement) (Fig. 19.7). It has been demonstrated that the rib level and lung volume in above functional residual capacity alter the rib compliance in caudal-cephalic direction (Wilson and De Troyer, 2004; De Troyer et al., 2005). Force transmission during diaphragmatic contraction creates a mechanical linkage between the lower and the upper rib cages (De Troyer, 2012).

Muscular actions during ventilation

The respiratory muscles have the same basic structure with other skeletal muscles. Any muscle that attaches onto rib cage may be considered to be a muscle of respiration (Muscolino, 2006; Özkal et al., 2016). However, major muscles of respiration composed of inspiratory and expiratory components. Inspiratory muscles induce inhalation by expanding the thoracic cavity. Muscles compressing the thoracic cavity are expiratory muscles, and they induce exhalation (Fig. 19.8).

Inspiratory muscles

The inspiratory muscles create a negative pressure in the thorax (Segizbaeva et al., 2013; Jones et al., 2016).

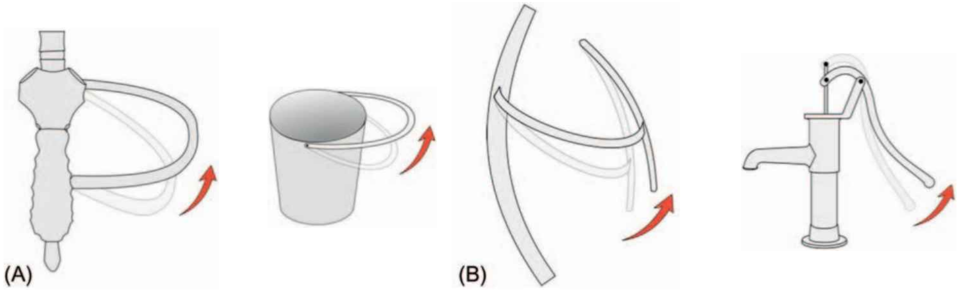

FIGURE 19.7 Rib movement during inspiration. (A) Bucket handle and (B) pump handle movements to increase transverse and anteroposterior dimensions, respectively.

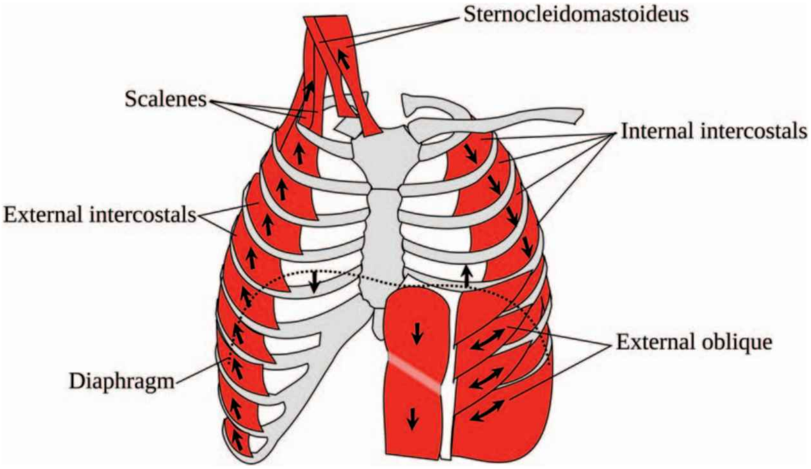

FIGURE 19.8 Muscle of respiration.

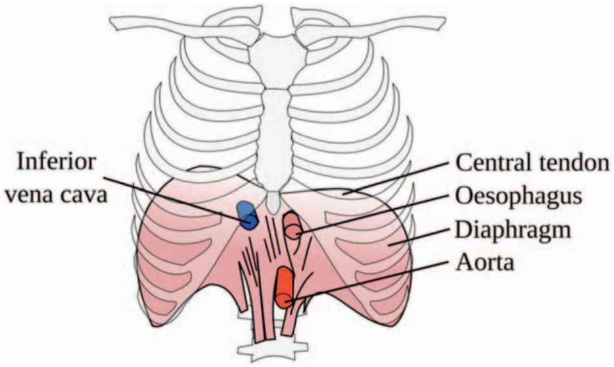

FIGURE 19.9 The anterior view of the diaphragm.

The diaphragm, scalene muscles and external intercostal muscles are the primary inspiratory muscles ensuring quiet inspiration. The diaphragm is a muscular dome-shaped structure. It attaches to the lower ribs and the lumbar vertebrae (Fig. 19.9). The diaphragm is derived from hypaxial musculature of cervical segments, and its motor innervation is from the right and left phrenic nerves (C3 to 5). There are ligaments called arcuate ligaments: median ligament, right and left medial ligaments, and lateral ligaments. Muscular structures of the diaphragm are right and left crura.

When contracts, the diaphragm flattens, moves downward into the abdominal cavity and increases the volume of the thoracic cavity. The movement of the diaphragm is about 1.5 cm during the quite respiration (Wade, 1954). The diaphragm moves downward until the central tendon becomes fixed. The contraction of the diaphragm also creates upward and forward movement of lower ribs. This movement also increases thoracic volume (Eichinger et al., 2007). Induced negative pressure is created proportional to the extent and force of the diaphragm when contracted. This may be altered in different postural conditions. The position changed from stand to supine influences the length of inspiratory muscles. The abdominal content displaces diaphragm upwards, diaphragm achieves a more advantageous position on the length-tension curve (Segizbaeva et al., 2013). While the diaphragmatic dome includes 43% of the muscular surface of the diaphragmatic area, centripetal forces result in an active peeling away of the diaphragm from the thoracic wall during contraction (Eichinger et al., 2007). There is a difference in excursion between the anterior and the posterior diaphragmatic regions. The anterior excursion is only about 60% of the posterior excursion. The diaphragm contributes to 60% of total inspiratory capacity (Eichinger et al., 2007). The 50–68% of VC is attributed to diaphragm displacement (Cluzel et al., 2000; Finucane and

Singh 2009). During inspiration, there is a broader shift on the right diaphragm compared to left side (Weckesser et al., 2006).

External intercostal muscles are the inspiratory muscles. Contraction of external intercostal muscles moves ribs to upward and outward. The external intercostal muscles also stabilize the rib cage and decrease the tendency to collapse. The scalene muscles attach to the top of the sternum, upper two ribs, clavicle, cervical vertebrae, and mastoid process. They lift the upper chest. The scalene muscles are considered to be primary muscles of inspiration because these muscles effectively lift and expand the rib cage (Segizbaeva et al., 2013). As the diaphragm flattens and the scalene muscles contract, the compression of the abdominal contents increases the intraabdominal pressure and in consequence facilitates the lateral pressure on the rib cage, causing expansion that contributes to the intrathoracic pressure changes that pull air into the lungs (De Troyer et al., 1982).

The diaphragm acts in a concert with the scalenes more passively than the abdominal wall. If "tone" or voluntary contraction exists, the intraabdominal pressure will be further increased resulting in better inspiration (Soderberg, 1997). The external intercostals are also considered as one of the primary muscles of inspiration. These muscles expand and elevate the costae for increasing the volume of the thorax. The pressure in the thorax decreases and relatively high-pressure exterior air flows into the low-pressure lung.

Deep breathing requires the contraction of the additional muscles of inspiration (sternocleidomastoideus, pectoralis major and minor, serratus anterior, serratus posterior, and upper iliocostalis), which is called auxiliary muscles (Reid and Dechman, 1995). The sternocleidomastoideus and parasternal muscles exert a force on the sternum, increasing the anteroposterior diameter of the upper rib cage during inspiration. If the glenohumeral joint is abducted to at least 90 degrees and fixed in this position, other thoraco-scapulohumeral muscles can assist with the elevation of the thorax (Soderberg, 1997).

Expiratory muscles

Quiet expiration is a passive process, controlled by the elastic recoil of the lung and the rib cage at the end of the inspiration. The conditions such as exercise involving forced expiration, requires the contraction of the expiratory muscles (internal intercostal muscles, rectus abdominis, lower iliocostalis, lower longissimus, serratus posterior inferior, and quadratus lumborum) to further decrease the diameter of the thorax. The primary and accessory respiratory muscles were demonstrated in Table 19.1.

Work of breathing

Work of breathing (WOB) is the energy required by the respiratory muscles to overcome the mechanical impedance to ventilation. The WOB can be partitioned between an elastic work (elastic recoil of lungs) and resistive work (airway resistance and viscosity of the lung and chest wall structures). In each respiratory cycle, WOB expressed as the change in pressure (ΔP) and the change in volume (ΔV), $WOB = \Delta P \times \Delta V$. The WOB is expressed in joules and requires typically 3–5% of total energy expenditure for the quite breathing. The work per liter of ventilation is the work per cycle divided by the tidal volume (Banner, 1995).

Mechanics of the respiration

The respiratory system is responsible for overcoming the elastic recoil and the airflow resistance in the airways to

TABLE 19.1 **Primary and accessory muscles of respiration.**

State	Inspiration	Expiration
Rest (primary muscles)	Diaphragm	**Passive process**
	External intercostals	*Elastic recoil of lung tissue*
	Scalenes	*Surface tension*
		Gravity
Forced (accessory muscles)	Sternocleidomastoideus	Abdominals
	Pectoralis	Iliocostalis (lower)
	Serratus anterior	Longissimus (lower)
	Serratus posterior superior	Serratus posterior inferior
	Iliocostalis (upper)	

enable ventilation. The mechanical properties of the lung tissue are divided into two main headings: elastic recoil and compliance.

The expanded lungs tend to return to the resting volume. The elastic structure, which was changed when a force was applied, tend to return to its original condition when the force decreases that is called elastic recoil of the lung. The elastic recoil depends on the amount of elastic tissue in the lung structure. At the end of expiration, the recoils of the lungs and chest wall are equal and in a balanced condition. At the end of the inspiration, the elastic recoil of the enlarged lungs pulls the chest wall towards the expiratory position. The elastic recoil pressure of the lungs (Pel) is defined as the difference between alveolar (Palv) and pleural (Ppl) pressure at any given lung volume, i.e., $\text{Pel} = \text{Palv} - \text{Ppl}$ (Gelb and Zamel, 2002).

Lung compliance is the capability to expand the lungs and thoracic cage. Static compliance is the change of volume per unit of change in the pressure across the lung. The dynamic compliance is also changed over time.

Surface tension, lung compliance, and airway resistance are the main factors affecting ventilation at rest (Longobardo et al., 1989). The force that called surface tension exerted by the liquid on the surface of the alveoli creates an inward force to reduce the surface area of the lungs. The high elastic properties of the alveoli allow their deflation as air is forced out during exhalation. Surfactant, a lipoprotein molecule, creates an air-fluid interface within the alveoli of the lung to reduce the surface tension, which is necessary to reduce work of breathing. Several alterations in surfactant metabolism may cause abnormalities in surfactant homeostasis. The reduction of the volume of fluid in the air-fluid interface with a decrease in the surfactant leads to atelectasis, while the reduction of the surfactant with the increase in fluid leads to pulmonary edema that is also called pulmonary congestion. Consequently, respiratory deficiency such as respiratory distress syndrome may also be seen. Respiratory distress syndrome (RDS) is the surfactant deficiency in preterm newborn infants; particularly, infants below 28 weeks of gestational age have immature lungs with severe deficiency of surfactant production (Chakraborty and Kotecha, 2013). Therefore, the surfactant homeostasis is necessary for preventing the risk of collapse of alveoli or pulmonary edema and enabling inflation and deflation properly.

Airway resistance is the force of the friction between the conducting airways and the flowing air. The geometric features of the airway and the properties of the flowing air determine the airway resistance. Airway resistance is inversely related to lung volumes and the diameters of the airways. Thereby, airway resistance is lower in a completely inflated lung than in an exhaled lung.

Respiratory system in different life stages: newborn, child, adult, and elderly

The differences anatomical and physiological structures in the respiratory system have an important role regarding its growth and development. The lungs go through four major stages: the embryonic period (gestational 3–5 weeks), the pseudoglandular period (gestational 6–16 weeks), the canalicular period (gestational 16–24 weeks), and the terminal sac period (gestational 24 weeks-term). In the embryonic period, the formation of the lung bud begins, and a single tube divides and creates two major bronchi. This period ends with the formation of major lung branches. In the pseudoglandular period, dichotomous are branched, forming airways from the trachea to the terminal bronchioles. Pulmonary circulation develops, cartilage and lymphatic formations occur, and cilia occur from ten weeks onwards. Respiratory bronchioles, alveolar canals, alveoli, and lung capillaries begin to form, and surfactant synthesis begins in the canalicular period between 24 and 34 weeks of gestational age (Nkadi et al., 2009; Chakraborty and Kotecha, 2013). In the terminal sac period, pulmonary circulation continues, and respiratory bronchioles are divided to form air cavities. Air cavities contain type I and type II pneumocytes. Type I pneumocytes form the lung surface area. Type II pneumocytes (2%) secrete and stores surfactant. After birth, the number of alveoli increases and their size grows (Joshi and Kotecha, 2007).

After birth, significant anatomical changes occur in the thoracic cavity. The differences in the respiratory system can be divided into anatomical and physiological differences in pediatrics and adults. The main anatomical differences are the structures of ribs and the shape of the thorax. These anatomical changes cause physiological differences. The neonate chest wall is more compliant compared to those of adults because of the cartilage structure of chest wall is in neonates. However, the thoracic stabilization during diaphragmatic contraction is weaker due to the immature nature of the intercostal muscles in neonates. The increased chest wall compliance and immature respiratory muscles in neonates engender the imbalance between the outwardly low chest wall recoil and normal inward elastic recoil causing the susceptibility to collapse.

Furthermore, the increased chest wall compliance frequently gives rise to the paradoxical inward movement of the thorax. As the infants grow, their posture becomes steeper, and their ribs become more oblique enabling to increase transverse diameter of thorax. Intercostal muscles are insufficient to increase thoracic volume by increasing anteroposterior/transverse diameter. The ventilatory requirement is met by the respiratory frequency, not by the depth of breathing (Jones et al., 2016).

The anatomical differences between infants and adults demonstrated comparatively in Table 19.2.

TABLE 19.2 The anatomical differences between infants and adults.

Structure		Infants	Adolescents and adults
Thorax	Shape of the cross-sectional area of the thorax	Cylindrical	Elliptical
Structure of costae	Bone formation	Not yet completed: costae soft and cartilaginous	Rigid chest wall
Position of chest wall structures	Ribs, sternum, and vertebral column	Horizontal position	Oblique
Costae movement	Bucket handle movement	Absent	Present
Larynx level		C3	Children: C4
			Adults: C5–6
Airway features	Length of trachea	4–9 cm	10–11 cm
	Diameter of trachea	4–5 mm	15–25 mm
	Narrowest part of the airway	Cricoid ring	Vocal cords
Cilia		Immature	Mature

The horizontal insertion angle of the diaphragm, less muscle mass, and less endurance of muscle fiber content in pediatrics cause mechanical disadvantage and predispose the infants to fatigue. Consequently, the alveoli are less in number and size making the infant lungs prone to collapse. Lambert channels connect the respiratory and terminal bronchioles to the alveoli and ducts connecting them into the openings in the alveolar wall. These alveolar openings are called Kohn pores. At birth, these pores do not exist; they develop at around four years of age and are found in highest numbers in the apical portions of upper and lower lobes. These differences limit the collateral ventilation in infants (Terry and Traystman, 2016).

The physiological differences between infants and adults summarized in Table 19.3.

The several changes occur in the respiratory system with age. These changes are a loss of elasticity and a decrease in elastic recoil, with the manifestations of a decrease in forced expiratory volume in one second, and vital capacity. The loss of elasticity also contributes to the early closure of small airways resulting in an increased residual volume and ventilation/perfusion mismatch with the advancing age. The aging causes decreased chest wall compliance, respiratory muscles weakening, and a decrease in muscle mass.

TABLE 19.3 Physiological differences between infants and adults.

Characteristics	Infants (features compared with adults)
Respiratory compliance	Higher chest wall compliance
	Lower lung compliance
Closing volume	Since closing capacity is larger than functional residual capacity in infant, the airway may collapse at the end of expiration
Ventilation and perfusion	In the infant, ventilation is better in the upper part of the lung and perfusion in the dependent regions. That is, there is more gas exchange in the upper parts of the lung, but there is an imbalance between ventilation and perfusion
Oxygen consumption	Increased resting metabolic rate in infants than in adults results in increased oxygen requirement
Muscle fatigue	55% type I fibers in adult diaphragm and 30% type I fibers in infant diaphragm
	Excessive muscle fatigue may result in apnea

Pathomechanics of the respiration

Chronic respiratory diseases intervene in the structure of the respiratory system by affecting the nature of the thorax, the lungs, and their mechanical and elastic properties. The diseases with the deterioration in the structure of the respiratory system could be classified as obstructive lung diseases and restrictive lung diseases based on the effects of airways and the ventilatory pump.

Obstructive lung diseases

The obstructive lung diseases cause structural changes in the lungs and thoracic cage due to inflammation. These structural changes provoke the overinflation of the lungs. The thoracic cage takes the position of inspiration causing the flat and low diaphragm. This position results in breathing at an increased volume to enable adequate gas exchange, which is challenging due to the present hyperinflation. The anteroposterior and transverse diameter of the chest is increased.

The expiration at rest is usually a passive process. However, in obstructive lung disease, with a change of the mechanics of thorax, the forced expiratory muscles must be actively contracted to drain the air out of the lungs and enable the diaphragm to return to its resting position (Yan et al., 1997). As the severity of disease increases, forced expiration requires higher intraabdominal pressure. The increase in intraabdominal pressure raises the stress on the pelvic floor causing urinary incontinence. The inspiratory muscle weakness leads the recruitment of accessory inspiratory muscles, including sternocleidomastoid, upper trapezius, the scalene muscles, and the pectoralis muscle group. The overuse of these muscles causes postural deterioration such as the anterior tilt of the head, rounded shoulders, thoracic kyphosis, and weakening and lengthening of the posterior thoracic muscles (Hillegass et al., 2017a,b).

Restrictive lung dysfunction

The restrictive lung dysfunction is characterized by the reduced lung capacity and ventilation due to the restriction of the chest wall and lung expansion. In these diseases, there is a decrease in the chest wall and/or lung compliance. The decrease of compliance induces the stiffness of the thorax and lungs resulting in the necessity of creating a greater transpulmonary pressure to enable the adequate lung expansion to a given volume. The patient need more effort to overcome this greater pressure which means the work of breathing increases. It is required to breathe at a higher respiratory rate with decreased tidal volume due to decreased compliance. While patients with obstructive lung diseases demonstrate impairments in expiratory mechanics, the patients with restrictive lung dysfunction demonstrate impairments in inspiratory mechanics. The expiratory flow limitation during rest is common in patients with chronic obstructive pulmonary disease but not in patients with restrictive dysfunction (Baydur and Milic-Emili, 1997).

Restrictive lung disorders can be classified as intrinsic (due to the inflammation or scarring of lung parenchyma before-mentioned as idiopathic pulmonary fibrosis, hypersensitivity pneumonia, pneumoconiosis or sarcoidosis) or extrinsic (due to extra-parenchymal diseases such as neuromuscular disorders affecting respiratory muscle function, or scoliosis, kyphosis, pleural effusions, phrenic

TABLE 19.4 Pulmonary function and mechanical parameters differences in obstructive lung diseases and restrictive lung disorders compared to the control subjects.

Parameters	Obstructive	Restrictive	
		Intrinsic	Extrinsic
Pulmonary function			
FEV$_1$	↓↓	Preserved or ↓	
FVC	Preserved or ↓	↓↓	
FEV$_1$/FVC	↓	Preserved or ↑	
RV	↑	↓	Preserved
FRC	↑	↓	
TLC	Preserved or ↑	↓	
RV/TLC	↑	Preserved	↑
Mechanical properties			
Airway resistance	↑	Preserved	
Lung compliance	Preserved or ↑	↓↓	↓
Chest wall compliance	↓	↓	↓↓
Total respiratory system compliance	↓	↓	↓

FEV$_1$: Forced expiratory volume in 1 s, FVC: Forced vital capacity, RV: Residual volume, FRC: Functional residual capacity, TLC: Total lung capacity.

neuropathies, muscular dystrophy, and other nerve and muscle disorders) (Coultas et al., 1994; Widmann et al., 1999).

Obstructive and restrictive lung diseases were summarized in Table 19.4 (Cherniack and Hodson, 1963; Faisal et al., 2016; Hillegass et al., 2017a,b).

In conclusion, the primary function of the respiration is a gas exchange of oxygen and carbon dioxide between the lungs and the blood. The activation of inspiratory muscles enables the expansion of the thoracic cage, and the air enters into the lungs while active muscle force is not required for the expiration during rest. Many variables such as lung and chest wall compliance, airway resistance, and surface tension affect ventilation. As the newborn and the children have different anatomical and physiological features of their lungs and chest wall, they have different characteristics of the respiratory mechanics compared to adults. Pathological conditions such as obstructive and restrictive lung diseases change breathing mechanics. Understanding the mechanics and pathomechanics of the respiration is essential for assessment and implementing proper treatment program.

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Chapter 20

Biomechanics of circulation

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Biomechanics of circulation

The most essential task of the cardiovascular system is to deliver the oxygen and nutrients, which are vital for the tissues, and to remove the metabolites and carbon dioxide. This is the basic mechanism in which the cardiac response occurs as fast as possible way in every situation that the body needs. Blood is composed of red-white blood cells (45%) and plasma (55%) (Baskurt and Meiselman, 2003; Popel and Johnson, 2005; Schmidt et al., 2016; Hall 2017; Pommella et al., 2017; Dawn and Kumari, 2018). 65−70% of the peripheral volume of the blood is located in the venous system (Kruse et al., 2016; Bappoo et al., 2017; Khan et al., 2017)

Biodynamics consist of three main factors: flow, stress and motion. The blood flow in vessels is laminar such as fluid in a pipe. The transfer of water, oxygen, carbon dioxide and other vital elements to tissues occurs by these three factors with different mechanisms through capillary cellular surfaces. By good understanding of residual stress, the effect of blood flow on heart and blood vessels can be interpreted through geometric analysis. Questions about bioregulation can be solved by mechanical principles that are applied to physiology of the circulation. There are still metabolic, neurologic and myogenic unresolved problems caused by local blood flow changes. Surface stress in endothelial cells is caused by pressure of the intravascular blood.

As a laminar model, blood flow is highest at the center and lowest on the surface of vessels. An object moving in the fluid is subjected to frictional force in the opposite direction. Smooth muscle cells of the heart work according to the Starling's Law. Whereas smooth muscle cells of vessels work according to the Bayliss phenomenon. Therefore, vascular smooth muscle cells do not show much change to surface stress forms. The difference in these muscles is the result of actin-myosin connections. Recently, in vivo experiments have revealed that ventricular muscles adapt to different situations in many ways. Current approaches will be covered in these chapters. It is important to know these principles for understanding the regulation of organ perfusion and circulation.

Biomechanics of heart as a pumping device

The primary cardiac function is to pump blood to distal organs and all the extremities of the body because of the ability of the ventricles and atria to fill with blood and contract. Biomechanics blood flow plays a critical role in regulating cardiac function not only in normal hearts but also in dysfunctional hearts. It is important to measure cardiac function. As well as, mechanical stress plays a critical role in the development of cardiomyopathies and LV remodeling post-MI, regulating tissue fibrosis and scar formation. During stresses in the heart due to hypertension it can also lead to hypertrophy of the ventricles and diastolic heart failure. Heart valve diseases, either stenosis or regurgitation also have a direct effect on the pumping function of the heart.

As the main body pump that works with auto impulse rhythm with sinoatrial node and its purkinje bundle, the heart is separated by interatrial and interventricular septa into four chambers as right and left atria and ventricles. According to normal human, blood flow generated by ventricular ejection is always unidirectional due to the function of the heart valves. The pulmonary valve and aortic valve prevent retrograde flow of blood back into the ventricles during diastole, while the tricuspid valve and mitral valve shut out reverse flow of the blood from the ventricle to the atrium during systole. Competent valves provide blood flow from high pressure chambers to low pressure according to gradients. Therefore, basically, two forces contributing blood flow from one point to another are the pressure gradient and the gravitational effect.

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The main body pump function can be evaluated at the cellular, tissue and organ levels, and at each level stress plays an important role in the regulation. Forces which oppose blood flow are the shear forces due to the viscosity of the blood and turbulences. The blood viscosity is determined by hematocrit, erythrocyte, leukocyte and platelet aggregation, and plasma viscosity. According to the velocity distribution, the blood is pushed through the vessels by the effect of laminar outward flow. The speed distribution is greater in middle than the edges. The sum of all these forces accelerates or decelerates the fluid in the vessels. According to fluid mechanics, fluids flow under constant shear stress, causing and this cause continuous shape changes. Stress is the force that acts on the unit area of the fluid. Stress is proportional to the change in unit of time. Fluid pressure follows the Pascal law (Baskurt and Meiselman, 2003; Popel and Johnson, 2005). In line with the shear stress, as the Newton's law, fluids change shape in direct proportion under constant heat. The shear stress occurs as a result of multiplying of the fluid viscosity and shear rate. In Newton's law, the viscosity in the laminar fluid flow is the ratio of the liquid layers or the shear stress to the laminate, the shear rate in the liquid, and the resistance force between the laminae (Schmidt et al., 2016).

The shear stress, thus drives adverse remodeling and contributes to the development of heart failure, is directly proportional to the flow velocity gradient between the layers. Visible viscosity in non-Newtonian liquids may decrease or increase depending on the shear rate. Blood is similar to a non-Newtonian fluid. Rheologically, blood is an incompressible and viscoplastic structured, multi-component liquid. The blood viscosity changes as the blood flow conditions change. As the shear stress decreases, the viscosity of the blood increases. Blood is an aqueous fluid that contains non-electrolytes, with cellular elements that make up 45–50% of the total volume. When the blood is centrifuged, it is divided into two parts, namely cells and plasma.

The fluidity of blood in ascending aorta creates increasing and decreasing speed by each heartbeat and results in turbulence. It is expressed as an average and continues to flow as a fluid. This movement integrity is maintained by creating turbulence. The force of gravity is extremely important. If blood flow stops, blood pressure will change according to the weight of the pool. The blood pressure at any point in the body is determined by gravity, loss of friction in the veins and pumping of the heart. Therefore, blood pressure in the human body changes with time and place. Under laminar flow conditions, it is fasted in the middle line and shows a parabolic-shaped reduction towards the sides with the effect of stress.

Atherogenesis forms major turbulent flow patterns in the aorta, as a result of plaque formation. Plaques can also take other abnormal blood flow forms. The energy is dissipated in turbulent flow. If total flow rate is unchanged and the laminate flow form turns into turbulent flow, the energy loss increases due to increase of the surface stress (Fig. 20.1). Atherogenesis can be produced from plaques formed by the buildup of fatty, calcified deposits in an artery (Fig. 20.2). The turbulent flow form is blunt and in a straight line in the center, sharpening and decreasing at the sides. Thus, the friction in turbulent flow is greater. Pressure changes the flow rates in the turbulent flow. Cardiac murmurs caused by intracardiac anomalies are turbulent sounds heard with a stethoscope. Owing to the continuity of current direction with respect to positive pressure gradient, valve surgeries and venous surgery operations can be done with careful attention to the flow direction. In arterial vascular operations, change of current direction and stenosis due to atherogenesis and plaque stabilization are very important for the development of ischemia.

During every cardiac cycle, there are typically two phases: systole, the period of active contraction, and diastole the period of relaxation and filling (Fig. 20.3). Mitral and tricuspid valves open to allow blood flowing into the ventricles. The two leaflets of the mitral valve open when the left atrium pressure rises above the left ventricular pressure and allow ventricular flow by the effect of jet flow. There is no backward flow or failure in normal valve design. Papillary muscles take an active role in opening and closing of the valve. Once cusps are closed, they support the geometry of the valve structure against the ventricular pressure.

In the isovolumetric state, closure of the valve against systole is maintained by positive pressure. With the same pressure gradient mechanism, aortic valve, venous and lymphatic valves open and close unidirectionally. The pressure between aortic valve and vena cava-right atrium is constituted by cardiac output besides resistance and is related to total peripheral vascular resistance. Systemic arterial pressure can be measured in this way. Although its direct

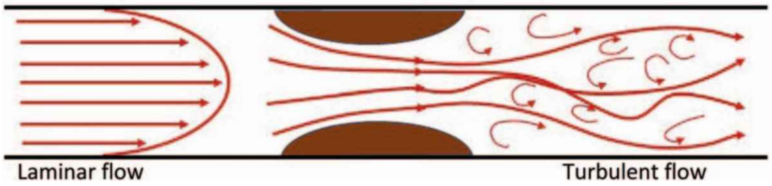

FIGURE 20.1 Laminar vs turbulant flow.

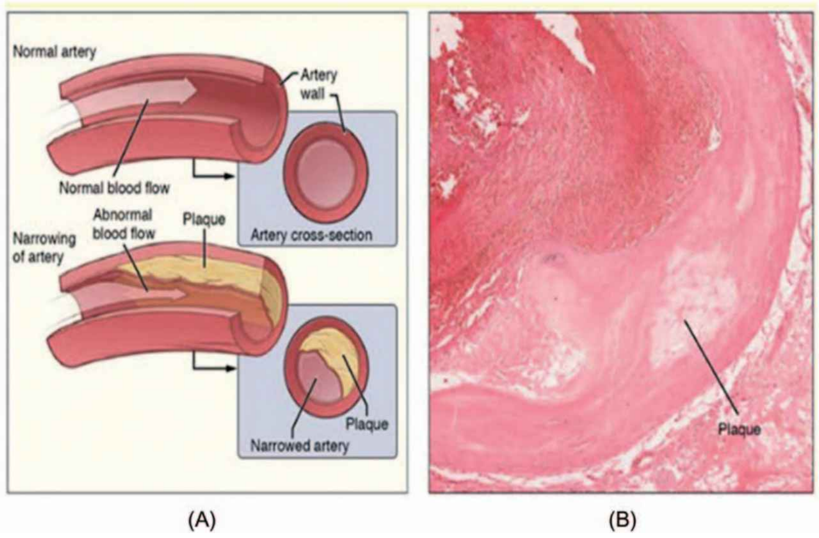

FIGURE 20.2 Model of (A) normal and (B) narrowed artery morphogenesis (Hall, 2017).

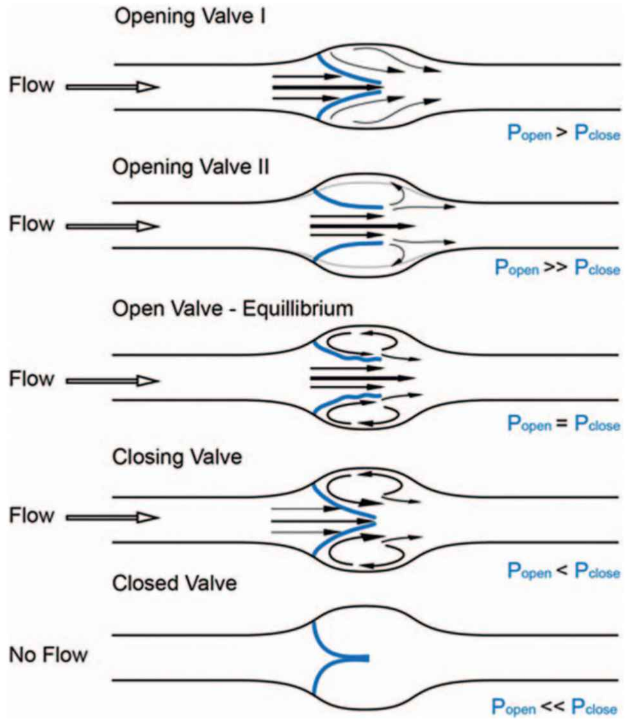

FIGURE 20.3 Fluid dynamics of a valve (Bazigou and Makinen, 2013).

measurement and calculation are complicated mean arterial pressure (MAP) can be approximated by adding the diastolic pressure to one-third of the pulse pressure or systolic pressure minus the diastolic pressure (Schmidt et al., 2016):

$$= + (-)3\text{MAP} = \text{diastolic BP} + 3(\text{systolic} - \text{diastolic BP})$$

In the systolic phase, when the right ventricular pressure is greater than the pulmonary artery and the left ventricular pressure exceeds aortic pressure, the blood flows through both the aorta and lungs. At the end of the jet flow, the valves are closed and the diastole phase begins by relaxation of the ventricles. The right atrium is filled with blood to a pressure of about 8–16 mmHg (Li and Cheng, 1993; Bazigou and Makinen, 2013; Dimakopoulos et al., 2015; Voorhees and Han, 2015). This phase is known as diastolic filling phase. In the left ventricle, there is almost 120 mmHg of pressure however, the difference between these phases in the aorta is lower than 120 mmHg due to its elastic structure (Schmidt et al., 2016). The mitral valve opens when the pressure around the aortic valve drops. When the aortic valve is opened during ejection, the orifice expands. This phase is known as systole. Mitral valve closes and valvular area is reduced. Vertical movement in the aortic valve sinus helps to fully close the valves with a turbulent effect. Until the valve is completely closed, this vertical movement continues from the left ventricle to the ascending aorta in the sinuses.

The blood flow in the body occurs due to the kinetic energy difference in the circulation between these two points. The resultant system of combining the potential energy, which presents in the cardiovascular circulation, with the kinetic energy generated by the heart, enables blood flow to continue. The kinetic energy across the cardiovascular system is less than that of the intraventricular area. But what makes the circulation continue; is the continuation of the blood flow to the low pressure area due to the kinetic energy imparted to the blood, even though the potential energy at the aortic valve during late injection falls below the intraventricular energy. This is due to increased kinetic energy.

During cardiovascular examination, diagnostic methods such as cardiac catheterization, echocardiography, and scintigraphy are used to perform diameter, and volume calculations in real sense. Changes in the arterial pressure do not immediately affect the cardiac output. According to the Starling's law of the heart, the most important factor is determining the cardiac output by a certain amount of blood entering the heart. The energy of the contraction of the heart depends on the length of the muscle fibers (Li and Cheng, 1993; Dimakopoulos et al., 2015; Voorhees and Han, 2015; Kruse et al., 2016; Bappoo et al., 2017; Khan et al., 2017; Pommella et al., 2017; Dawn and Kumari, 2018). As the end-diastolic volume of the heart increases, the contraction increases as the ventricle also increases in tension. This arrangement, which occurs by changing the size of the sarcomeres, is heterometrically regulated. When the amount of blood increases in the diastole, the cardiac metabolism also increases because of excessive work load on the cardiac muscle the heart, and the heart muscle fibers turn to homeometric condition, which is not related to length of the fiber. When we look at the solid mechanics of the heart, the stretching behavior of the left ventricular wall muscles under stress and tension is in accordance with the Hooke's law (Schmidt et al., 2016; Hall, 2017). The length of the heart muscle fibers is proportional to the end-diastolic volume. Hooke's law explains that the decay of a substance is approximately proportional to the applied force. That is, tension is directly proportional to the strain of the ventricle. End diastolic volume load is the main influence determining the tension. According to that stress state, the endocardium is exposed to this tension. The elongation of the heart wall occurs as the result of the extension of the sarcomere length in the heart muscle cell. More ATP consumption and calcium requirement occur in the endocardial area. The coronary capillary blood flow of this region should be supported more intensely. In cases of acute ischemia due to coronary vessels, thinning occurs in the left ventricular wall. Systolic dysfunction develops as collagen accumulation occurs in this scarred region. Cardiac re-modeling occurs if reperfusion is performed.

The heart responds to changes in exercise more quickly than any other organ in the body (Li and Cheng, 1993; Dimakopoulos et al., 2015; Voorhees and Han, 2015; Kruse et al., 2016; Bappoo et al., 2017; Khan et al., 2017; Pommella et al., 2017; Dawn and Kumari, 2018). Muscular activity accelerates the flow of venous blood towards the heart. Exercise response is formed by the increase in heat generated by the cutaneous vasodilatation and increase in the blood flow rate. As a result of active vasodilator response, blood exchange with the blood transfer to tissues reaches maximum after 10–15 minutes after exercise. When the rectal degree exceeds 37.5 degrees Celsius, the heart rate increases at 25.7/min °C shots (Voorhees and Han, 2015). 0.42 beats/s is accompanied by an increase in heart rate as long as the rectal degree increases (Fig. 20.4). Each red blood cell contains 29 picograms of hemoglobin and is chemically transported with heme units and 4 diatomic oxygen (Voorhees and Han, 2015). Respiratory system responds to exercise more slowly than cardiovascular system. Unlike the respiratory system, there is a limit to respond to exercise in the heart. Aerobic metabolism should be increased by at least 50% when exercise exceeds 120 seconds (Voorhees and Han, 2015). Anaerobic metabolism is required for the system even at maximum oxygen intake for respiratory muscles at peak exercise level. This increases blood lactate levels, making anaerobic metabolism difficult for muscles and causing fatigue.

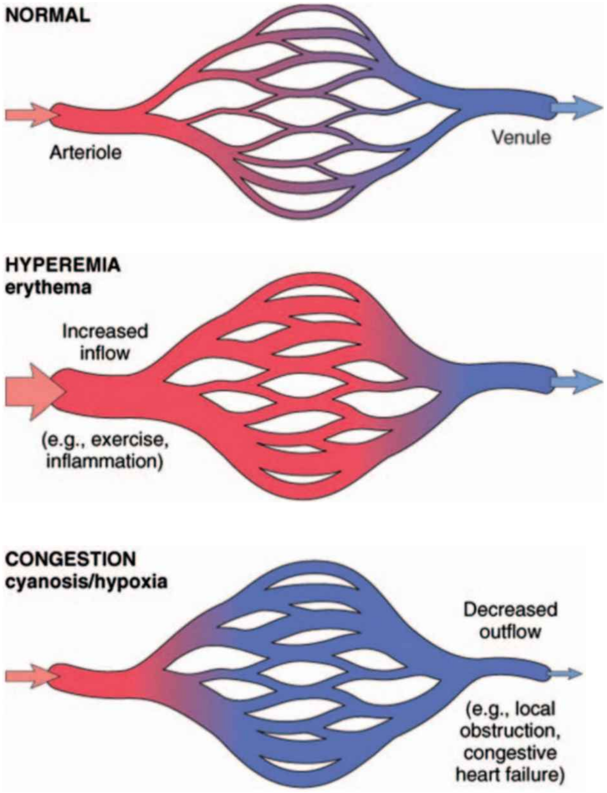

FIGURE 20.4 Model of arteriole and venule morphogenesis (Kumar and Abbas, 2018).

Biomechanics of blood flow in arteries and veins

Biomechanics of blood flow in arteries and veins provide a tool to understand the mechanism of left ventricular remodeling in diastolic and systolic dysfunction and guidance in designing and developing new treatment strategies (Fig. 20.5). The effects of mechanical stress on ventricular wall remodeling and cardiac function regulate the wall mechanical properties on cardiac function in normal and

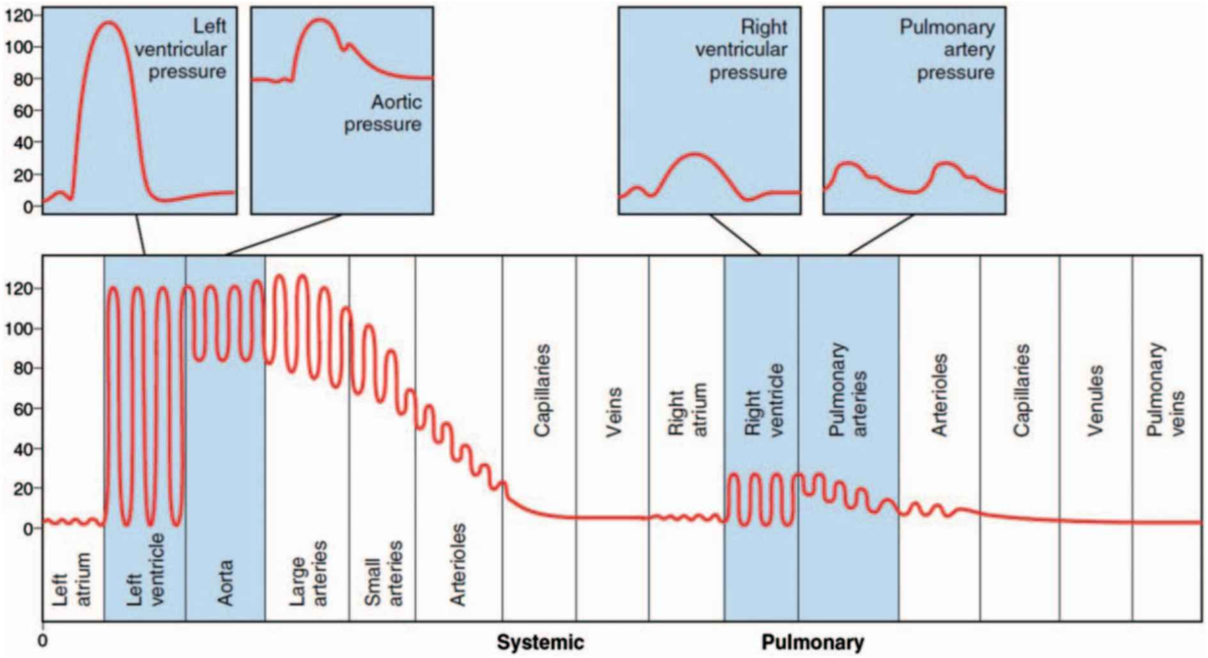

FIGURE 20.5 Flow control in our vessels. Elsevier - Guyton's physiology (Hall, 2017).

dysfunctional hearts. Many atypical conditions may affect the complex pumping system of the heart and can be caused by a variety of factors including genetic, aging, and environmental factors.

According to the Bernoulli's law, the pressure will be less where the velocity is slower in the horizontal flow than in the points where it is faster (Pommella et al., 2017). It is explained by the kinetic energy of motion and the potential energies of weight. Fluid flow is accelerated towards a region where the pressure is lower, from a region where the pressure is higher (Fig. 20.6). With this law, pressure transducers and flowmeters can be used for intravenous measurement. Between normal aorta and vena cava, this law can be neglected because there are no other potential energies and no flat flow form, but there is a significant increment in friction-induced pressure and energy loss in capillary vessels smaller than 100 μm that is called microcirculation. Hagen-Poiseuille law describes the motion of a laminar flow fluid (Dawn and Kumari, 2018). According to this law; a horizontal flow of a frictional fluid is proportional to the pressure difference between the vessel sections. In the Poiseuille law, the basic structure that determines the motion of a fluid is resistance. Therefore, the resistance in parallel flows is lower than the serial flow resistances. Resistance is expressed as the ratio of the pressure to the flow. According to the Poiseuille's law, 2-fold vasodilatation causes ~ 16-fold variation in resistance. The smooth muscle of the arterial structure in the cardiovascular system, the valvular character of the venous structure and their flexibility contribute to the regulation of cardiovascular resistance.

Biomechanical aspects of the atherogenesis can be explained as the effect of the liquid and solid on atherogenesis is defined. Endothelial cell surface stress caused by blood flow results in vessel remodeling. In veins, collapse may occur; flow stabilization via longitudinal tension caused by tube form results in enlargement. Flow variances, compressible structure and turbulent flow are mostly studied. Capillary microcirculation is essential. Moreover, in pulmonary flow, the effect occurs via waterfalls phenomenia between capillary and vein stage.

Gas exchange in the interalveolar septas occurs by a drop in pressure at the end units of these capillaries and venous structures, resulting in a mutual interaction. Moreover, Waterfalls phenomena occurs via stucked effect between coronary capillary and cardiac muscle in the heart. The interaction between the muscle cell and the capillary blood vessels is specific. Waterfalls phenomenon is similar in striped muscle cells, but heart muscle cells are more compressed (Schmidt et al., 2016).

There are various receptors for impulses in cardiovascular control. Carotid sinus and aortic arch stretch receptors, in each pulmonary artery bifurcation baroreceptors, left and right atrium are available in the volume receptors (Li and Cheng, 1993; Dimakopoulos et al., 2015; Voorhees and Han, 2015). Carotid and aortic receptors mainly provide arterial pressure protection. In addition, chemoreceptors in these regions provide response to emergency situations in pO_2, pCO_2, ph changes.

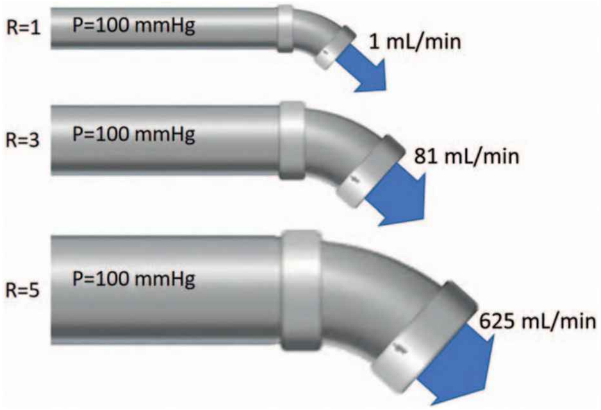

FIGURE 20.6 Demonstration of the effect of vessel pressure on blood flow.

Pulmonary inversion receptors originate from the vagal afferents. The heart also takes innervation from the vagus. The vagus nerve plays a role in cardiac output and cardiac involvement in heart-lung interactions. In dive and nasal circulatory reflexes, trigeminal nerve somatic impulses are involved (Li and Cheng, 1993; Dimakopoulos et al., 2015; Voorhees and Han, 2015). All peripheral blood vessels are under sympathetic autonomic nerve stimulation. Arterial pressure and tissue blood supply are regulated. Veins are involved in the storage and capacitance of blood. Venoconstriction and arterioconstriction occur together and the blood shifts to the arterial side. With vasoconstriction, the blood supply to the gastrointestinal tract, kidneys, liver, and spleen is reduced. During exercise, blood flow to the muscles decreases by 30% blood flow to the lungs and skin (Voorhees and Han, 2015). During exercise, stroke volume usually does not increase; it is accompanied by an increase in total peripheral resistance. Biological stress is involved in regulating cardiomyocyte function and extracellular matrix structure that controlling body function (Bazigou and Makinen, 2013). The heart also pumps blood to maintain circulation and ensures the delivery of oxygenated blood to all the organs of the body. Biomechanics play a critical role in regulating heart function under both normal and pathological conditions.

Blood rheology defines the flow and influence of blood and blood constituent elements (Khan et al., 2017). In addition, blood and vessels interaction with foreign body is essential. Fluids continuously deform or flow. So the viscosity of the blood plays a vital role in blood rheology. Deforming force is surface stress. Shear stress is the force acting on the vessel surface parallel to the unit area. Under the effect of this force called the shear stress, blood moves. Reynolds number is smaller in small veins (Kruse et al., 2016). The blood flow in microvessels is more influenced by viscosity. Reynolds number in fluid mechanics is the ratio of a fluid's forces to its viscosity forces and as a result, this value determines the deformation of the shaped elements of the blood under the influence of these two forces. The Reynolds number is a parameter used to decide whether a flow is laminar or turbulent. The resistance results in a frictional ending that occurs along the entire inner surface of the vein. The flow of blood can be calculated according to the Ohm's law (Kruse et al., 2016; Bappoo et al., 2017). Resistance, vessel diameter and blood viscosity are proportional. The blood flow increases as the pressure increases and decreases as the resistance increases. As the blood viscosity increases, the flow rate in the arteries and veins decreases. In hypertension, cerebrovascular diseases and peripheral vascular diseases, Diabetes, Atherosclerosis, Sickle cell anemia and Polycythemia blood rheology is adversely affected. Atherosclerosis can be built up with injury to the endothelium of an artery, which can be caused from high blood glucose, infection, tobacco use, excessive blood lipids, and other factors like hypertension. Artery walls are constantly stressed by blood flowing in hypertension.

From arteries to veins, blood flow is reduced. The blood viscosity falls when the vessel diameter is less than 300 μm. There is a sharp decrease in blood flow in the 5−7 μm diameter capilleries. This effect is called the Fahraeus Lindqvist effect (Dimakopoulos et al., 2015; Bappoo et al., 2017). The effect of the Fahraeus-Lindqvist fits the flow in the capillaries. Movement toward the center of the vein is accelerated by erythrocyte deformability, and the rigidity of the cell is reduced. Erythrocytes and other granular cells show viscous behavior. Erythrocytes move in flow. At high shear rates, erythrocyte deformability increases. Between the two erythrocytes the plasma fluid makes rotational movements. At this time, the plasma fluid accelerates the exchange of substances from the walls. This movement of blood is called bolus flow. The number of excess vessels, small vessel diameter and length leads to a pressure gradient. Small arteries and arteriole-resistant vessels. This anatomic structure leads to vasodilation or vasoconstriction during blood flow with diameter change. Capillary pressure drop varies between 5 and 10 mmHg. Capillaries do not have smooth muscle and thus can not be actively dilated or contracted. The surface area of the capillaries is sufficient for exchange with the bloodstream in the tissues. Peripheral vascular circulation surface area is 70 m^2 (Li and Cheng, 1993; Schmidt et al., 2016).

Biomechanics of blood flow in lungs

Blood flow in the aorta and its branches and gas exchange in the lungs with trachea and airflow in their branches continues to work in coordination. The main task of the lungs is oxygenation of the blood and removal of carbon dioxide. For this biochemical reaction, the blood must contact a very large surface area at microcapillary level. In adult lung, pulmonary capillary blood volume is 150 ml, capillary gas exchange area is 70 m^2, and capillary surface thickness is 4 μm (Pommella et al., 2017). This thin membrane surface separates blood from the air with a distance of 1 μm (Pommella et al., 2017).This intermediate layer consist of interstitium with endothelial and epithelial cells. The smallest unit of interalveolar septa is called alveolus. It is estimated that the human body has 300 million alveoli (Schmidt et al., 2016; Pommella et al., 2017; Dawn and Kumari, 2018). This special structure aims gas exchange from the atmosphere. All alveoli are polyhedral. Blood vessels must transport erythrocytes through the network of these capillaries to the ventilation units, in sufficient quantities and in certain transition time. For oxygenation, hemoglobin should move from alveolocapillary membranes to erythrocytes and plasma.

Pulmonary blood flow occurs as well as right ventricular pressure. Pulmonary circulation blood passes from the right ventricle to the alveolar-capillaries through the pulmonary arteries (11–25 mmHg). Blood return is directed to the left atrium through pulmonary veins (2–7 mmHg). Pulmonary arterial pressure is 10–25 mmHg and pulmonary venous pressure is 4–5 mmHg in larger veins. The structure of pulmonary artery is weaker when compared to the aorta and exposes to lower pressures.

In addition, pulmonary capillary arteries are highly flexible compared to systemic arterial structures (Kruse et al., 2016; Khan et al., 2017). Therefore, gas exchange can be done easily. Pulmonary arterial and venous pressures at the beginning of pulmonary apex are almost equal in the upright position. Main factors determining pulmonary blood flow are; vascular wall topology, alveolar gas and blood pressures, blood viscosity due to hematocrit and other factors, elasticity of vessels, intrapleural pressure and lung capacity. The lung has a wide lymphatic network and nerve structure as organ structure. The lung has a complex structure that can function through chemoreceptors. In the case of hypoxia there is a potential neural and humoral response mechanism. Catecholamines, histamine and serotonin are alerted to discharge quickly. The pulmonary arterial and venous system enlarges and blood circulation increases. In chronic conditions, the maximum organ response is obtained by adding collateral vessel formation to increase circulation.

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Part 6

Lower extremity

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Chapter 21

Kinesiology of the hip

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Introduction

The hip joint is an amphiarthrosis joint that moves in three planes as a pivot point. At the intersection of these three planes, the movement centre of the hip joint is formed. The ball-like femoral head and surrounding acetabulum allow movement of the pelvis and femur relative to each other. Movement, such as lifting the foot from the ground, laying on a surface or rapidly turning the body in a single limb, occurs due to special and strong muscle activation around the hip (Neumann, 2010a,b). The hip joint acts as a base for the pelvis and body movements while managing lower extremity movements, and kinesiologically dominates the majority of body movements.

The hip joint is a highly stable joint that can perform flexion, extension, adduction, abduction, external rotation, internal rotation and circumferential movements. The femoral head is fixed by a deeply enclosed socket. The stability of the hip joint is provided by the joint capsule rather than the surrounding muscle structure. This fixation provides stabilization many activities we do during the day such as walking, standing, running (Neumann, 2010a,b). Acute injuries, chronic degenerations or surgeries that alter the kinematics of the hip affect the function of the hip during activities.

The pelvis should also be considered when referring to the hip joint and its kinesiology. The pelvis has three important functions. The first of these, it acts as a common connection point for many large muscles in the trunk and lower extremity. The pelvis conveys the upper body weight to the ischial tuberosities in the lower extremity while sitting, standing or walking. In addition, it supports the pelvic floor, pelvic muscles, connective tissue, bowel and bladder as well as reproductive organs.

Hip traumas and injuries are more common in older people than in younger ones. However, owing to congenital reasons, an infant may also develop hip dislocation. An elderly individual is generally vulnerable to degenerative joint disease. Along with an increased risk of falls, osteoporosis also increases the tendency of hip fractures in the elderly.

When physiotherapists create rehabilitation programmes for patients with hip trauma or pathologies, they need to have sufficient knowledge about hip and pelvis anatomy and kinesiology as well as ligaments, muscle weaknesses and hip movements on various planes on the pelvis and femur.

Acetabulum

The round, deep pit on the medial and external sides of the coccygeal bone is called the acetabulum. This pit forming the concave joint surface of the hip joint is constituted by os ilium, os ischium and pubis. The bodies of the ilium, ischium and pubic bone are joined by Y-shaped triradiate cartilage and ossificate at approximately 14–16 years of age to form acetabulum, which is the joint pit on the external surface of the coccyx. The edge of the acetabulum is called limbus acetabuli. The deep notch at the underside of this edge, which is not fully ring-shaped, is called incisura acetabuli. Behind it lies the ilioischiadic notch, whereas in the front lies the ischiopubic notch. The incisura acetabuli continues upwards with the fossa acetabuli, which does not contain any joint surface. Between the fossa acetabuli and limbus, acetabuli lies the crescent-shaped facies lunata, which is 2-cm wide, covered with hyaline cartilage and is the part that comes into contact with the femoral head. It is also the thickest part of the acetabulum. The acetabulum forms the hip joint by joining with the femur head. The upper edge is the most circular edge of the acetabulum. However, the depth of this

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structure only covers the femur by 170°. The labrum is a fibrocartilage structure made up of collagen fibrils that circumferentially adhere to the acetabular edge; further, it increases the depth of the acetabulum. The labrum, inferolaterally continues with the transverse acetabular ligament, which crosses the acetabular notch and becomes thinner at the superior of the acetabulum towards the load-bearing surface (Larson et al., 2005). Through a histological study, Seldes et al. reported that the labrum was joined to the acetabular cartilage with a 1–2 mm transitional zone (Seldes et al., 2001). Blood is ensured to the labrum via a vascular cascade of superior and inferior glutaeal arteries as well as an obturator artery, which penetrates through the periphery of the labrum and crosses the surrounding cavity, as in the acetabular bone (Seldes et al., 2001). The labrum is innervated by branches of the quadriceps femoris muscle and sensory branches of the obturator nerve. Demyelinated nerve endings are more remarkable in the superficial layer. Nociceptors and mechanoreceptors are also present in the labrum (Kim and Azuma, 1995). The medial part called acetabular fossa does not have articular cartilage. Its bone structure is thin and it does not take part in articulation; further, it is covered with fat tissue and pulvinar and serves as an insertion site for ligamentum teres. The acetabulum socket inferiorly terminates with the transverse ligament, which then turns this notch into a hole by attaching to the edges of the acetabular canal. Vessels and nerves coming to the joint pass through this point.

Centre-edge angles: First time measurement by Wiberg; the lateral incision of the femoral head by the acetabulum is measured in the frontal plane on plain radiograph. Normally it is 26° ± 6°. The small angle indicates the shallowness of the acetabulum, while the large angle values indicate the deep acetabulum values (Tonnis, 1987). Femur in children under eight ossifying the determination of the centre of the head the closest point to the growth cartilage of the nucleus suggested to be taken as the centre point (Inan et al., 2006).

Femoral head and neck

Proximal femur includes the femoral head, neck and the region 5-cm distal to the lesser trochanter. There is a 125°–130° inclination angle between the head and neck and the femoral body. Further, there is a 15° anteversion angle between the plane passing through the condyles of the femoral head and the femur neck. The portion of the femur articulated with the acetabulum is approximately two-third of this sphere. In normal hip, the centre of the femoral head exactly coincides with the centre of the acetabulum. Fossa capitis femoris (fovea) is medially located at the top of the femoral head, where the ligamentum teres is attached (Ito and Minka, 2004). Greater trochanter is intersectioned at the junction of the body and femoral neck, where the abductor muscles are attached. Furthermore, in normal hip, the top of the major trochanter is at the same level as the centre of the femoral head; the lesser trochanter lies under the femoral neck along the inner back surface of the femoral body. Iliopsoas muscles attach at this point.

Ligamets of the hip joint

The joint capsule is attached to the edges of the acetabulum, transverse acetabular ligament and femoral neck. While superior anterior parts of the capsule thick and strong, it is thin and loose at the posterior and inferior regions. Intracapsular and extra-capsular ligaments increase stability of the hip joint in both static and dynamic conditions as well as provide support for joint capsule.

Ligamentum teres (foveal ligament)

The ligament of the femoral head is the only intracapsular ligament. It is a relatively small structure extending from the acetabular fossa t fovea capitis the femoral head. It encloses a branch of the obturator artery (femur head of the artery), which is a minor arterial supply to the hip joint.

The three primary extra-capsular ligaments continuous with the external surface of the hip joint capsule are as follows (Fig. 21.1):

Iliofemoral ligament

It is one of the strongest ligaments present in the body. It originates from the anterior inferior iliac spine and attaches to the intertrochanteric line. It limits thigh and body extension as well as thigh adduction (Taner, 1996).

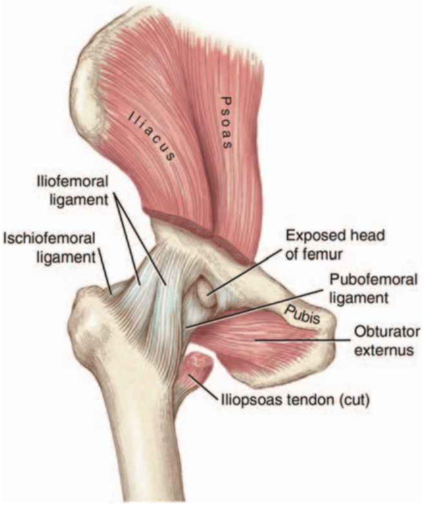

FIGURE 21.1 The anterior capsule and ligaments of the right hip (Neumann, 2010a,b).

Ischiofemoral ligament

It originates from the lower back portion of the acetabulum and encloses the femoral neck. It limits thigh and body extension as well as thigh pronation (Taner, 1996).

Pubofemoral ligament

It originates from the iliopubic eminence and obturator crest and attaches to the internal edge of the intertrochanteric line. It limits thigh and body extension as well as thigh hyperabduction (Taner, 1996).

Muscle dynamics

Although not as much as that of the shoulder joint, the hip joint's range of motion is also quite large. When the knee joint is flexed, the femoral region resting versus the abdomen area restricts hip flexion movement. When the knee is extended, stretching of the hamstring muscles limits hip flexion. Evaluation of the muscles surrounding the hip revealed that external rotation muscles are stronger than internal rotation muscles.

Hip joint movement involves flexion, extension, adduction, abduction and rotation within special physiological limitations of soft tissues. Flexion is restricted to the hamstring muscle group. Tensor fascia lata, iliotibial band and gluteus maximus form the superficial muscle layer. In the next layer, glutaeus minimusand medius link to the large trochanter and the overlying fascia by anteriorly and posteriorly enclosing the hip joint capsule. On the posterior side, short external rotators (piriformis, obturator internusgemellus superior, gemellus inferior and quadratus femoris) surround the articular capsule and enter the medial part of the trochanteric prominence from the proximal to the distal end. Although rectus femoris transverses the hip joint just like hamstrings, the main dynamic stabilizers include glutaeal muscles (glutaeus minimus, medius and maximus), iliopsoas, adductor muscles, tensor fascia lata and deep muscle structures as well as the iliotibial band (piriformis, pectineus, obturator internus and externus, superior and inferior gemellus). These deep muscle hip structures are thought to be the 'rotator cuff' muscles of the hip and possess 'fine tuning' roles in hip movements (Ekşioğlu et al., 2011). Figs. 21.2 and 21.3 show muscles of the HIP.

Piriformis muscle

While sacrum is stable, it brings the femur to external rotation, abduction and flexion. Further, while the femur is stable, it contributes to pelvic extension by bilateral

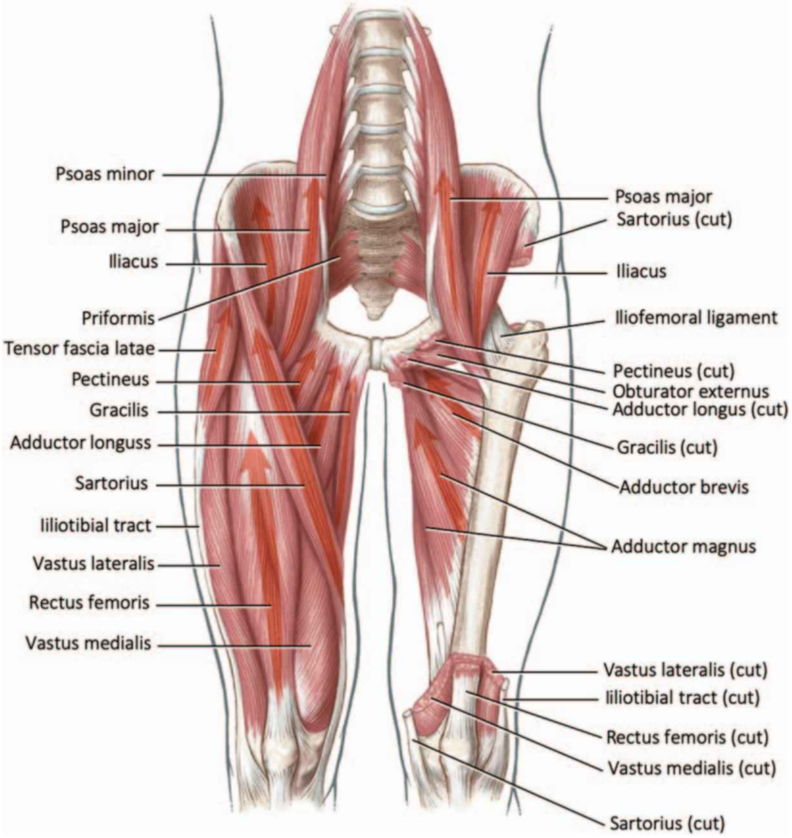

FIGURE 21.2 Muscles of the anterior hip region (Neumann, 2010a,b).

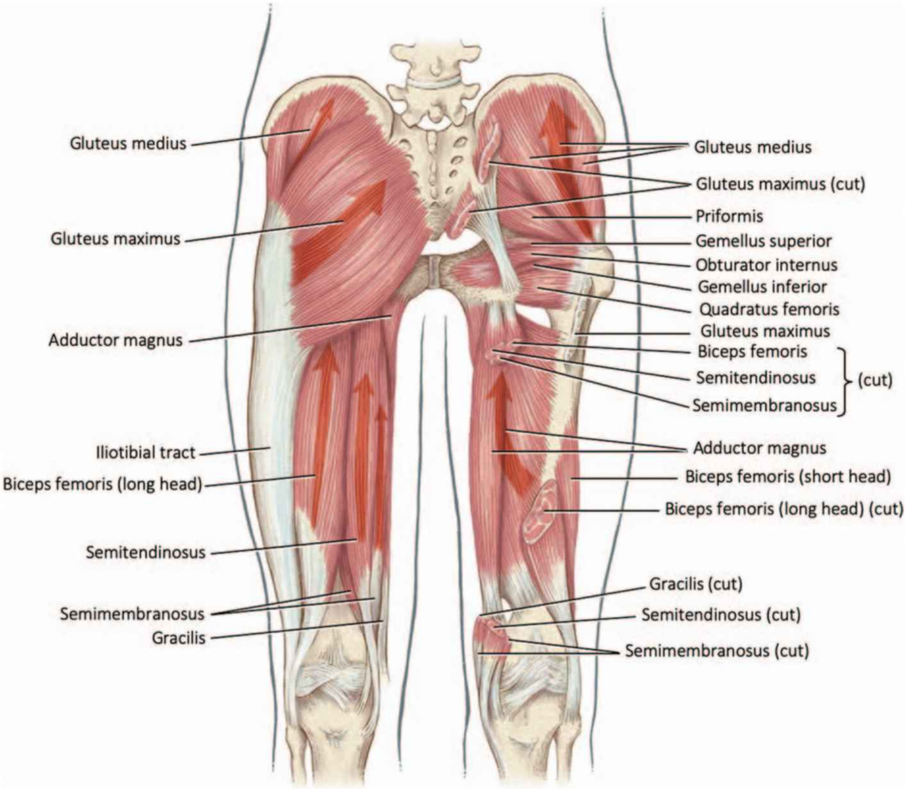

FIGURE 21.3 Muscles of the posterior hip region (Neumann, 2010a,b).

contraction. Unilateral contraction contributes to internal rotation of the pelvis (Ekşioğlu et al., 2011). Piriformis muscle is innervated by the sacral plexus (L5—S2).

Quadratus femoris muscle

While the pelvis is stable, it brings the thigh to external rotation. It bilaterally contracts while the femur is stable and supports pelvic extension. Unilateral contraction contributes to internal pelvic rotation (11). Quadratus femoris is innervated by the inferior glutaeal nerve and sacral plexus (L5—S2).

Obturator internus muscle

While the pelvis is stable, it brings the thigh to external rotation, flexion and abduction. It bilaterally contracts while the femur is stable and extends to internally rotate the pelvis (Ekşioğlu et al., 2011). Obturator internus is innervated by the inferior glutaeal nerve and sacral plexus (L5—S2).

Obturator externus muscle

While the pelvis is stable, it brings the thigh to external rotation, flexion and abduction. It bilaterally contracts while the femur is stable and brings the pelvis to flexion. Its unilateral contraction plays a role in the internal rotation and flexion of the pelvis (Ekşioğlu et al., 2011). Obturator externus is innervated by the obturator nerve (L1—L4). When looking at the hip from the right side, the obturator externus muscle runs anteroinferiorly as the obturator internus and gemellus muscles posterioinferiorly stretch after originating from the greater trochanter. The following are observed as a result of the joint actions of the obturators and gemelli muscles:

- While the pelvis is stable, these muscles pull the femur downwards relative to the pelvis.
- While the femur is stable, these muscles pull the pelvis upwards relative to the femur.
- The obturators and gemelli muscles support the pelvis like a hammock.

In both cases, these muscles tend to ‘pull apart’ the hip joint, even if it is small-scaled. In some painful conditions (such as in cartilage abrasions), this is a very useful decompressive effect (Ekşioğlu et al., 2011).

Psoas major muscle

While the vertebral column is stable, psoas brings the hip to flexion and also acts as a weak adductor and external rotator (Ekşioğlu et al., 2011). Psoas major is innervated by lumbar plexus and the femoral nerve (L1—L3).

Iliacus muscle

When the pelvis is stable, it brings the hip to flexion, just like psoas major. It bilaterally contracts while the femur is stable and brings the pelvis to flexion. An important point to be considered is that superior attachments are completely different. While the femur is stable, iliacus acts on the pelvis, whereas the psoas major acts on the lumbar vertebrae. The iliacus and psoas are called as one single muscle 'iliopsoas' because they have the same tendon and exert the same movements to the thigh (Ekşioğlu et al., 2011). The iliacus is innervated by the lumbar plexus and femoral nerve (L2–L4).

Gluteus minimus muscle

Its most important function is to strengthen the anterior part of the glutaeus medius. Apart from exerting abduction to the thigh, it also helps in flexion and internal rotation. When bilaterally contracted while the femur is stable, the glutaeus minimus helps pelvic flexion and external rotation; it also helps lateral flexion or external rotation in unilateral contraction (Ekşioğlu et al., 2011). The glutaeus minimus is innervated by the superior glutaeal nerve (L4–S1).

Gluteus medius muscle

While the hip is stable, its main function is hip abduction. However, it helps in flexion via its anterior fibers and extension via its posterior fibers. When the femur is stable, the glutaeus medius plays a role in both flexion and extension of the pelvis, depending on the contraction of the anterior or posterior fibers when it is bilaterally contracted (Fig. 21.4). Its main function is observed when the person is standing on one foot, which involves lateral flexion of the pelvis. When it is unilaterally contracted, it provides lateral flexion of the pelvis and stabilises it when walking or standing on one foot (Ekşioğlu et al., 2011). The gluteus medius is innervated by the superior glutaeal nerve (L4–L5).

Tensor fascia lata muscle

This muscle exerts abduction, flexion and internal rotation to the thigh. It also plays a minor role in extension or external rotation while the knee is flexed. While the thighs and legs are stable, it plays a role in flexion of the pelvis when bilaterally contracted and in external rotation or lateral flexion when unilaterally contracted (Ekşioğlu et al., 2011). Tensor fascia lata is innervated by the superior glutaeal nerve (L4–L5).

Gluteus maximus muscle

Deep layer: While the hip bone is stable, it pulls the femur in the posterior direction during light adduction and external rotation (hip extension). While the femur is stable, it plays a role in the extension of the pelvis when it is bilaterally contracted and in internal rotation and medial flexion of the pelvis when it is unilaterally contracted.

Superficial layer: 'Pelvic deltoid muscle' superficial layer of the glutaeus maximus (at the posterior) and tensor fascia lata (at the anterior) inserts on the iliotibial band in opposite directions. The superficial layer of the glutaeus maximus plays a role in the extension, abduction and external rotation of the femur. The tensor fascia lata muscle brings the femur to flexion, internal rotation and abduction. Both muscles simultaneously assist the glutaeus medius in maintaining the contralateral pelvis position while standing on one foot. These two muscles work in synchrony to bring the hip to abduction. If the femur is stable, they assist in the lateral flexion of the pelvis (Ekşioğlu et al., 2011).

Adductors: The primary action of this muscle group is to adduct the hip. To a lesser extent, they play roles as hip flexors and external or internal rotators in the

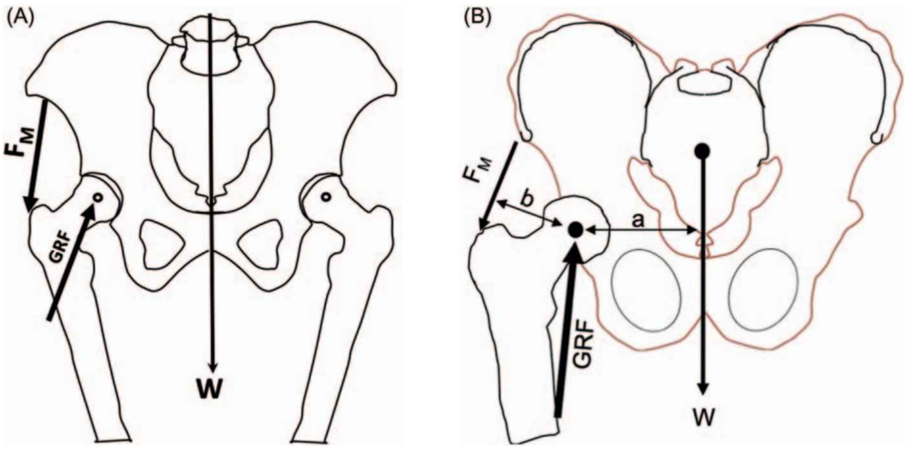

FIGURE 21.4 (A) The load on each hip is sum of one-third of the total body weight and the force exerted by muscles around the hip joint. (B) Hip joint loading during unilateral stance. Weight of unloaded lower extremity = 1/6 BW; total body weight on the hip = 5/6 BW; muscle force lever arm (a) = 0.1 m; gravity force lever arm (b) = 0.05 m; load exerted by muscle (FM) = 2(5/6 BW); ΣF = GRF (ground reaction force) = (5/6BW) + 2(5/6BW).

anatomic position. They function as extensors when the hip is flexed. Polyarticular gracilis muscles also bring the knee joint to flexion and internal rotation. While the femur is stable, adductors take part in flexion, medial flexion, external rotation or internal rotation (when posterior of the gracilis and adductor magnus are contracted) of the pelvis (Ekşioğlu et al., 2011).

Hip joint biomechanics

Hip joint biomechanics may be defined by considering joint kinematics or kinetics (Callaghan et al., 2007). Joint kinematics defines angular or translational movements made by the joint in response to applied force. Joint kinetics indicates the forces and momentum acting on the joint during movement between the acetabulum and the femoral head and, particularly in the contact phase of walking. This balance is provided by opposite forces that exist between the centre of gravity of the body and the abductor muscle force. At the different stages of the gait cycle, area being loaded on the femoral head changes as the direction and magnitude of ground reaction force change. Anterosuperomedial region is under load when the heel touches the ground, whereas posterosuperolateral region is under load when the heel is lifted off the ground.

The hip joint is affected by static and dynamic forces while standing and walking. In a normal person standing in an anatomic position on both legs, the equal load acts on both hips (Yücetürk, 2007). In a normal hip joint, there is a functional balance in the static position. The load on each hip is sum of one-third of the total body weight (Pauwells, 1976) and the force exerted by muscles around the hip joint (Fig. 21.4A). In the swing phase of walking, when the extremity in one side is lifted off the ground, the weight of that side will be added to the body weight and the centre of gravity will shift to the opposite side and will no longer pass through the centre of the body. The load on the hip joint should be much higher than the body weight. The force generated in the hip joint, which in a sense constitutes the support point of the lever, is equal to the sum of momentums (Yücetürk, 2007). For the balanced pelvis in a load-bearing hip, the abductor muscle force must create counter-momentum two times higher than the momentum of the body weight (Pauwells, 1976). Therefore, during unilateral stance, hip joint receives load that nearly three times of body weight (Fig. 21.4B).

The forces on the hip joint will also be affected in the presence of surgical procedures or diseases that cause changes in joint anatomy.

Movements of the hip joint

The hip joint is spherical and can move in three dimensions in space. Joint movements are defined by rotations and translations in x, y and z planes. When measuring joint kinematics, rotations are implied in practice, because the translation rate is quite small and it is difficult to measure it using biomechanical analyses. These are flexion–extension rotation in the sagittal axis, abduction–abduction rotations in the frontal axis and internal–external rotations in the vertical axis. When the pelvis is stabilised in the neutral position, hip flexion is approximately 120° and extension is 10° (Johnson and Pedowitz, 2007). Internal rotation and external rotation occur at the centre of the femur head and around the longitudinal axis passing through the intercondylar area in the distal part. The average total range of motion is 50°. Average internal rotation is 15° and external rotation is 35° (Johnson and Pedowitz, 2007). Femur rotation with respect to the midline of the body in the frontal plane constitutes the abduction and adduction movements. When the hip is in extension, abduction is 45° and adduction is 25° (Johnson and Pedowitz, 2007).

Inclination Angle: This angle increases the strength and movement of the hip joint and exerts incoming force on a larger area. During childhood, average inclination angle is 160°, and in most adults, this angle is approximately 125° (varies between 90° and 135°). Coxa valga develops if the angle is greater than 125°, whereas coxa vara develops if the angle is smaller than 125°. The effect of muscles creating abduction on this angle is important. Coxa valga develops if the abductor muscles are insufficiently exercised during early ages, whereas coxa vara develops if they are over exercised.

Anteversion Angle: This angle is formed by a line projecting from the transverse axis of the femur condyles and longitudinal axis of the femoral head (Fig. 21.5). In adults, this angle is approximately 12° on average; however, it greatly varies. When the angle is greater than 12°, some part of the femur head cannot be covered, and the leg is internally rotated to maintain the femur head in the acetabulum while walking. When the angle is smaller than 12° (retroversion) (Fig. 21.5). the leg is externally rotated while walking. These two situations are quite common in children but disappear as they grow. An increase in bone density in the subchondral region of the acetabulum is seen in the anterior–posterior graph of the normal hip joint. This region represents the actual load-bearing surface. Although the three-dimensional anatomical structure of the surface is in a sloping, semilunar shape, a circular image similar to the shape of a bow is observed on the graph. The line connecting the lateral and medial sides of the normal hip load-bearing surface is located in the horizontal plane. Two trabecular structures extending upwards from the load-bearing surface are observed on the anteroposterior view; one starts from the inferomedial of the acetabulum and extends towards the anterior superior iliac spine, whereas the other extends from the lateral lip of the acetabulum to the posterosuperomedial of the sacroiliac joint. An arched structure similar to that of an hourglass is formed when these two arcs join. In a normal hip joint, the line connecting the top of the arched structure to the centre of rotation of the femur head is perpendicular to the horizontal plane of the load-bearing surface and passes from its mid-point. A spherical section is formed if the centre of rotation of the femur head and the medial and lateral edges of the load-bearing surface are connected. This section indicates the portion of the femur head under load. Bombelli assumes that, even in a normal hip, such a change is sufficient for the development of osteoarthritis in an active person (Bombelli, 1983).

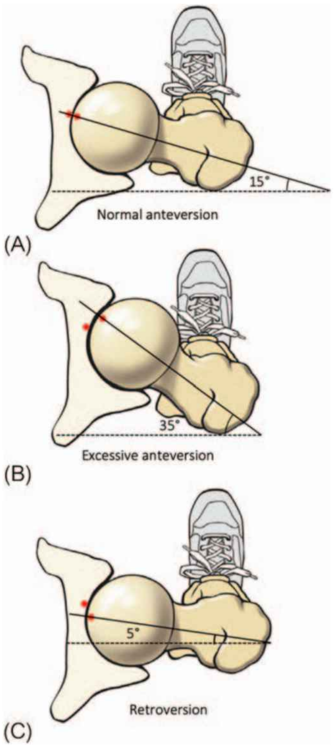

FIGURE 21.5 (A) Normal anteversion; (B) excessive anteversion; and (C) retroversion (Neumann, 2010a,b).

The hip joint moves independently from the pelvic girdle but is completed by the pelvic tilt. Unlike the shoulder joint, it is impossible for the right side to move independently of the left in the pelvic girdle. In the upright position, the horizontal angles of the upper and lower openings of the pelvis are 15° at the top and 50°–60° at the bottom. These angles are called ‘pelvic inclinations.

Two terms are generally used in hip kinematics: osteokinematics of the femur on the pelvis (rotation of the femur relative to the fixed pelvis) and osteokinematics of the pelvis on the femur (rotation of the pelvis relative to the fixed femur). Osteokinematics of the femur or pelvis are designated according to the anatomical positions as flexion and extension in the sagittal plane, abduction and adduction in the frontal plane and internal and external rotation in the horizontal plane.

Femoral movements on the pelvis

Hip flexion and extension occur in the sagittal plane with rotation of the femur on the pelvis (Fig. 21.6). The hip flexion is nearly 120° during knee flexed. the main capsular ligament is relax when hip is full flexion, but inferior capsule and muscles (gluteus maximus etc.) are stretched together. Hip’s range of flexion is restricted 70°–80° during the knee extension. This movement is restricted by tension on the hamstring muscles. Hyperextension of hip is approximately 20°. During full hyperextension, the iliofemoral ligament’s and other the capsular ligament’s tension, and flexor muscle’s tension increase. If the knee is fully flexed, rectus femoris is stretched and so hip extension reduces (Neumann, 2010a,b).

Hip abduction and adduction occur in the frontal plane with rotation of the femur on the pelvis (Fig. 21.7). Hip abduction and adduction are approximately 40 and 25,

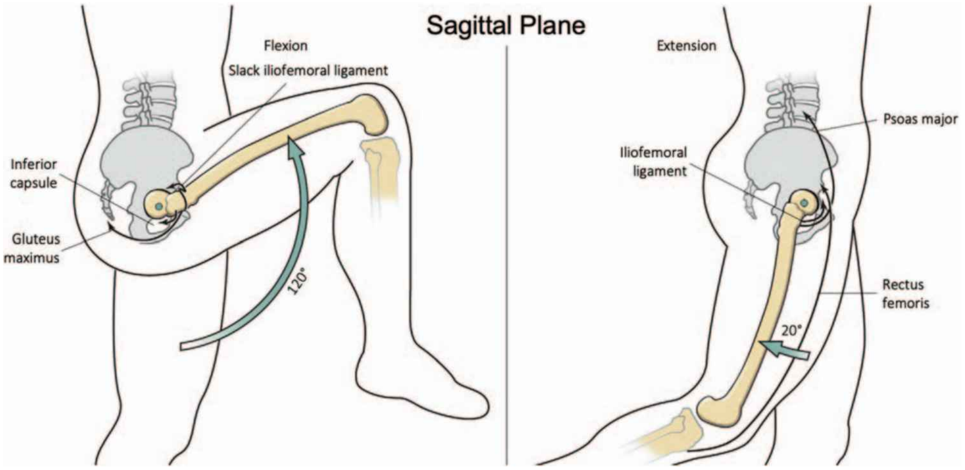

FIGURE 21.6 Sagittal plane hip motion- flexion and extension (Neumann, 2010a,b).

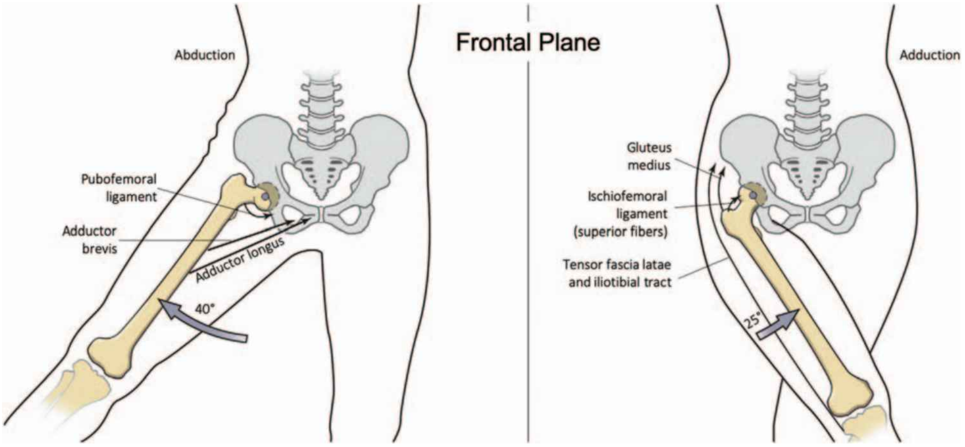

FIGURE 21.7 Frontal plane hip motion- abduction and adduction (Neumann, 2010a,b).

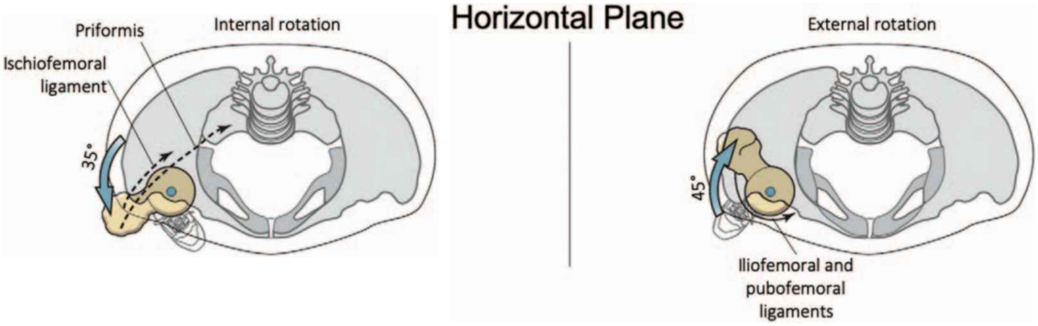

FIGURE 21.8 Horizontal plane hip motion- external rotation and internal rotation (Neumann, 2010a,b).

respectively. Abduction is restricted by pubofemoral ligament and hip adductor muscles. And adduction is restricted by hip abductor muscles, iliotibial band, and superior ischiofemoral ligament fibers (Neumann, 2010a,b).

Hip external rotation and internal rotation occur in the horizontal plane with rotation of the femur on the pelvis (Fig. 21.8). Hip internal and external rotation is approximately 35 and 45, respectively. External rotation is restricted by lateral parts of iliofemoral ligament, and internal rotator muscles (Roach and Miles, 1991; Simoneau et al., 1998).

Pelvis movements on the femur

The pelvis is important bone in human body in terms of locomotion. It makes stability of muscles that are origin from here is provided. In addition there is relationship with axial skeleton to keep balance. Another role is that transfer the body weight from the skeleton to lower extremities via the pelvic girdle when standing, or to the ischial tuberosities when sitting (Palastanga and Soames, 2012).

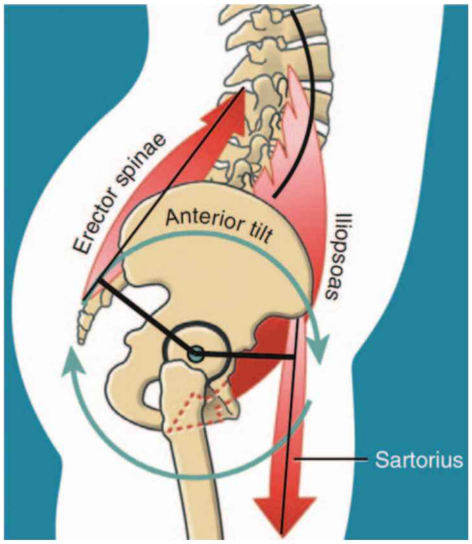

FIGURE 21.9 Anterior pelvic tilt (Neumann, 2010a,b).

The rotation direction of an iliac crest determine pelvic tilt direction on the sagittal plane. During anterior pelvic tilt, hip flexion occurs and the rotation axis for the tilt goes through the femoral heads, as a result the lumbar lordosis increases (Fig. 21.9). The normal adult can perform an additional 30° of pelvic-on-femoral hip flexion in sitting position with the hips 90° flexion, and further movement is limits by lumbar spine extension. The iliofemoral ligament and other most hip ligaments decrease tension in full anterior pelvic tilt. If the hamstrings are tight, anterior pelvic tilt can be restricted by the hamstrings while knee extension (Neumann, 2010a,b).

Posterior pelvic tilt enables the hips to be extended 10°–20° at the sitting position. This rotation movement increases length and tension of iliofemoral ligament and rectus femoris muscle minimally. Flexion and flatten are seem in the lumbar spine during posterior pelvic tilt (Neumann, 2010a,b) (Fig. 21.10).

During standing on the one extremity, the iliac crest is raised on the other side with the support hip abduction. If the supralumbar trunk keeps immobile, it is necessary for the lumbar spine to bend in opposite direction of rotating pelvis. Resulting lateral lumbar convexity occurs towards the abducting hip.

The natural limit of lateral lumbar spine bending is nearly 30°, and restricted with pelvic-on-femoral hip abduction. This movement can also be limited by tight hip adductor muscles and the pubofemoral ligament. Significant contracture in the hip adductor muscles leads to landing of the nonsupport hip's iliac crest compared that of the support hip and interferes with walking. Support hip adduction develops with nonsupport hip iliac crest landing, which also causes lumbar region lateral concavity on the adduction side. As a result, some motion may be limited by a hypomobile lumbar spine and/or decreased iliotibial band or abductor muscle stretch (Neumann, 2010a,b).

Pelvic-on-femoral rotation occurs around a longitudinal axis of rotation in the horizontal plane. When the pelvis is rotating and the trunk is as far as fixed, the lumbar spine rotates in the across direction to the pelvis. However, the lumbar spine can normally move a little axial rotation and this movement limits full rotation of the support hip on the horizontal plane. Therefore, full movement requires both the lumbar spine and trunk to match pelvic rotation. This movement can be occurred with an ipsidirectional lumbopelvic rhythm (Neumann, 2010a,b).

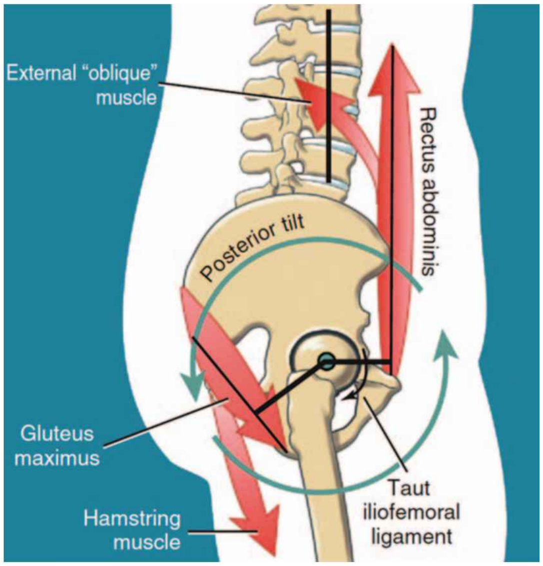

FIGURE 21.10 Posterior pelvic tilt (Neumann, 2010a,b).

The hip joint during walking and running

In the standing position the centre of gravity is through the rotation centre of the hip. The anterior section of the capsule (iliofemoral ligament) thickens and the static standing position is provided mostly by ligament support instead of muscle contraction.

Pauwels has concluded that there is equal load on both hips when both feet are on the ground. Normally the body weight goes in front of the second sacral vertebra and through the middle of the pelvis when both feet are on the ground; however, with a single foot on the ground, the centre of gravity shifts towards the other foot as it is lifted (Pauwels, 1980). When walking, the antero-supero-medial femur head carries the load on heel contact and the postero-supero-lateral part at the beginning of the swing phase (Bergmann et al., 2001). It has been possible to dynamically measure the loads on the hip in several studies. During slow gait, the load on the hip joint is approximately three times the body weight following heal contact and four times the body weight when the toes are being lifted. During rapid gait, these loads increase less markedly than the body weight. When skiing, the load on the hip joints is approximately 4 to 12.4 times the body weight (Paul, 1966; Morrison, 1968; Novacheck, 1998; Winter, 2009).

Understanding hip kinematics is quite important when correcting a deformity. For example, it must be known that the abductor lever arm is shortened in the case of coxa valga and the hip joint will increase the reaction strength as acetabular coverage may decrease while in the case of acetabular dysplasia, the stress on the load bearing articular cartilage will increase. In such cases, the femur head coverage should be increased with pelvic osteotomy if necessary and the abductor lever arm needs to be lengthened with a proximal femoral varus osteotomy.

The range of motion of the hip joint has been measured in all planes with electrogoniometric methods in various studies. During a normal stride, the hip rotates approximately 40° in the sagittal plane. Maximum hip flexion of 30°–35° occurs at about 85% of the gait cycle in the late swing phase and maximum extension of 10° at approximately 50% of the cycle at near the toe-off position (Baggaley et al., 2015). Hip adduction occurs throughout the early stance, reaching a maximum at 40% of the cycle, while hip abduction of 5°–7° is observed in the early swing phase, in the frontal plane. Perry has found a total transverse plane motion of 8° 30. The maximum value of internal rotation is seen near the midstance position and the hip rotates externally during the swing phase

Baggaley et al have found no relationship between the femoral neck-shaft angle and hip adduction in their study on the hip kinematics in the frontal plane when running. They also did not observe a relationship between the pelvis width-femur length ratio and hip adduction (Baggaley et al., 2015).

Proprioceptive and kinesthetic issues of hip region

The neuromuscular control and the dynamic stability of the hip joint are provided by the proprioceptors and the tractuses. It includes peripheral mechanoreceptors that determine signals and transmit proprioceptive information to the sensory cortex of the brain (Gardner, 1948; Paul 1966; Morrison 1968; Paul 1976; Roach and Miles, 1991; Novacheck, 1998; Simoneau et al., 1998; Bergmann et al., 2001; Palastanga and Soames, 2012; Baggaley et al., 2015).

Afferent-efferent feedback systems help to improve movement coordination and postural control to help prevent injuries. It was found that there was a relationship between the reduced number of nerve endings and proprioception deficits in the joint disease (Hurley, 1999). Dynamic joint stability is affected by Proprioceptive system performance and Proprioceptive system performance may be a contributing factor to joint cartilage degeneration. Moraes et al. (Moraes et al., 2011) showed that there was a significantly greater reduction in the Pacini type mechanoreceptors ($P < 0.035$) than in the Ruffini type mechanoreceptors among individuals with hip arthrosis and lower overall mechanoreceptor densities. People with knee osteoarthritis often have sensory deficiencies in the lower extremities, defined as proprioceptive loss, loss of balance, loss of joint position sense, and kinesthetic loss (Hurley, 1999; Nyland et al., 2015). The role of these deficiencies in the pathophysiology of joint with OA is not clear, but an increasing number of evidence offers that decreased sensory input may impair or decrease protective muscular reflexes around the joint, leading to enhanced mechanical loading and articular cartilage damage. Shakoor et al. showed that significant sensory deficiencies related to hip osteoarthritis and these deficiencies included both the upper and lower extremities. The mechanism for this remains unclear; however, the mechanisms of neurologic feedback or an inherent generalized neurologic failure has been suggested (Shakoor et al., 2008).

Hip pathologies

The neuromuscular hip

Neuromuscular disorders commonly lead to changes in the hip joint due to the muscle imbalance they cause. This disturbance can be subluxation or dislocation or even degenerative arthritis that can be painful and require surgery.

Hip dysfunction can be caused by intrinsic or extrinsic factors. Intrinsic problems develop during childhood while extrinsic problems can occur in stable hips and lead to degenerative arthritis with muscle imbalance playing a secondary role. Hip instability is usually due to strong hip flexors and adductors and weak or absent abductors and extensors. Other causes can be coxa valga due to anatomic variations and soft tissue contractures and increased femoral anteversion or increased acetabular index.

Neuromuscular disease patients may require hip problem treatment for the disease itself and the resultant hip dysplasia (e.g., due to cerebral palsy (CP) or myelomeningocele) and degenerative arthritis.

Developmental dysplasia of the hip (DDH)

The anatomical changes seen in the DDH depend on the type and degree of the condition and the patient's age. The disorder is progressive and characterized by anatomical changes that are reversible at first (Nimityongskul et al., 1995). Major changes occur in the acetabulum while secondary changes occur in the femur (Weinstein et al., 2004). If the DDH is left untreated for a long time, the capsule, soft tissues, acetabulum and femur head become deformed (Weinstein, 1996). In untreated cases where the femur head has a partial relationship with the acetabulum, the femur head moves upwards and downwards on the oblique acetabular surface. This unstable condition leads to degenerative changes such as subchondral sclerosis, cystic changes, osteophyte development on the femoral head and joint cartilage loss in the late adolescent period (Karapinar et al., 2002). If the hip is left dislocated until the adult period, the femur head is settled quite high on the acetabulum. The joint capsule becomes extremely thick. The femur head becomes oval and is flattened medially. The acetabulum is filled with fibrous tissue. The joint cartilage is atrophic or absent. The muscles adhering to the proximal femur are extremely short. Degenerative changes are not seen in fully dislocated hips (Abu Hassan and Shannak, 2007). In the subluxated unstable hip, the joint capsule is flaccid and the ligamentum teres is elongated, the labrum is rotated externally and the femur head is normal. There is increased anteversion of the femur head in the acetabulum and femur leading to an unstable hip, in the end increasing the pressure inside the acetabulum and disturbing the femur head centralization (Kashiwagi et al., 1996). The femur head in subluxated hip cases loses its spherical structure. Acetabular and femoral anteversion are increased. The acetabulum is shallow, and deformation starts on the posterosuperior aspect. The fibroadipose tissue mass increases in the acetabulum and the subluxated hip becomes irreducible due to intraarticular changes. The femur-acetabulum relationship is completely deranged, and the femur head is displaced posteriorly and superiorly. The acetabular roof loses its concavity, becomes oblique and creates a convex surface. The pressure of the dislocated femur head on the ileum results in differentiation of the ileal periosteum into fibrocartilaginous tissue and it covering the ileum to create a false acetabulum.

Changes in the capsule

The articular capsule and the surrounding ligaments are found to be lax. As the femoral head moves further away from the acetabulum, the capsule is elongated and become tubular. The transverse acetabular ligament is drawn upwards with the capsule as the femur head is displaced upwards, becomes hypertrophic and prevents reduction by blocking the lower part of the acetabular cavity. The trochanter minor is displaced upwards and crosses the anterior aspect of the iliopsoas tendon capsule that adheres here. The tendon therefore thins the capsule by compressing it externally and the thinner midsection of the capsule creates the isthmus with an "hourglass" deformity, resulting in a significant obstacle for closed reduction (Kashiwagi et al., 1996; Milgram and Tachdjian, 1976).

Ligamentum teres

In the dislocated hip, the ligamentum teres is elongated and thickened. It fills and occupies space in the acetabular cavity and prevents reduction (Weinstein et al., 2004; Connolly and Weinstein, 2007).

Pulvinar

This is a fibroadipose structure on the acetabular base and is generally adherent to the ligamentum teres and prevents reduction (Weinstein et al., 2004). In prolonged cases, it leads to flattening of the acetabular lodge by causing hypertrophy.

Limbus

In the normal acetabulum, this is a fibrocartilaginous structure that adheres to the labrum acetabulum margin as a triangle with a free top. The concave side surrounds the femur head while the convex side continues with the capsule and synovium. As the femur head is displaced upwards, the labrum rotates externally and is crushed between the head and the iliac wing. The mechanical stimulus caused by the dislocated femur head leads to an increase in fibroblasts and fibrous tissue development at the acetabular cavity margin. The fibrocartilage acetabular labrum can only be differentiated histologically from the hyaline cartilage of the acetabulum (Milgram and Tachdjian, 1976). The limbus can at first be corrected when the hip is reduced. In delayed cases, the acetabular margin of the hardened limbus has to be removed without damage so that it does not prevent reduction (Schilt, 2004).

Femoral-pelvic muscles

The displacement of the femural head leads to contracture through shortening of the muscles and fascia around the joint. The hip abduction that is important position after hip reduction surgery becomes more difficult due to adductor contracture. Upward displacement of trochanter major leads shortening of the gluteus medius and the minimus muscles. Contracture could also be developed on the priformis muscle. The iliopsoas is shortened and closes the anterior passage of the acetabulum by compressing the capsule (Dezateux and Rosendahl, 2007).

Femoral head changes

The delay in the ossification of the proximal epiphysis that starts to be noticed 4–6 months after birth is another pathology in developmental dysplasia of the hip (DDH). The postero-medial surface flattens and becomes mushroom shaped (Gala et al., 2016; Chadayammuri et al., 2016). Almost all cases with DDH have various degrees of increased femoral anteversion up to 60°–90°. In the end, when the dislocated head is re-centralise into the acetabulum, the lower extremity turns medially (the patella faces internally.) This causes instability and may result in new dislocation or subluxation at the neighboring joints (Ross et al., 2011).

Acetabular changes

The hips are in the flexion and abduction position in the intrauterine period but convert into the extension and adduction position in the post-natal period and the femur head enables pitting of the acetabulum through compression. In case of DDH, the acetabular anteversion increases and the femural head coverage decreases, the acetabular roof becomes more oblique and the concavity is disturbed (Wiberg, 1939).

As a result of frontal inclination of the acetabulum, the femural head is prone to leave the acetabulum. In this case, the stimulus pitting the acetabulum is eliminated and the acetabulum becomes shallow (Chadayammuri et al., 2015). Acetabular dysplasia is a deformity that develops as a result of the loss of the normal relationship between the femural head and the acetabulum. The acetabular dysplasia that is minimal in the newborn period, however, progresses to dislocation. The acetabulum develops until 8 years of age, and an acceptable acetabulum development can be ensured if the femoral head is centralised by the age of 4 (Fujii et al., 2011) (Table 21.1).

TABLE 21.1 Muscles of the hip, organized according to primary or secondary actions.

Muscles	Primary	Secondary
Flexors	İliopsoas Sartorius Tensor fasciae latae Rectus femoris Adduktor longus Pectineus	Adductor brevis Gracilis Gluteus minimus (anterior fibers)
Ekstensors	Gluteus maximus Adduktor magnus (posterior head) Biceps femoris (long head) Semitendinosus Semimebranosus	Gluteus medius (middle and posterior fibers) Adductor magnus (anterior head)
Eksternal Rotators	Gluteus maximus Priformis Obturator internus Gemellus superior Gemellus inferior Quadratus femoris	Gluteus medius (posterior fibers) Gluteus minimus (posterior fibers) Obturator externus Sartorius Biceps femoris (long head)
İnternal Rotators	Not applicable	Gluteus minimus (anterior fibers) Gluteus medius (anterior fibers) Tensor fasciae latae Adductor longus Adductor brevis Pectineus Adductor magnus (posterior head)
Adductors	Pectineus Adductor longus Gracilis Adductor brevis Adductor magnus (anterior and posterior heads)	Biceps femoris (long head) Gluteus maximus (posterior fibers) Quadratus femoris Obturator externus
Abductors	Gluteus medius (all fibers) Gluteus minimus (all fibers) Tensor fasciae latae	Priformis Sartorius Rectus femoris

Each action assumes a muscle is fully activated from the anatomic position. Several of these muscles may have a different action when they are activated outside of this reference position (Neumann, 2010a)

Hip joint in cerebral palsy

In children with CP, hip deformities are very common problems. The hip-related risks in these children include subluxation, dislocation, degeneration and pain-related dislocation. The spastic hip dysplasia seen in CP differs from developmental hip dysplasia (Fujii et al., 2011). Table 21.2 shows that comparison of spastic hip dysplasia and developmental hip dysplasia.

While the hip joint is normal at birth, it starts to change with growth. Excessive muscle tonus results in constant force that causes deformation in the proximal femur and acetabuim in the growing hip. Spasticity or contracture are generally seen in the adductors or iliopsoas muscles and causes subluxation of the femoral head towards the posterosuperior direction. The centre of rotation of the hip is displaced towards the trochanter which is lower than the centre of the femural head (Chadayammuri et al., 2015).

Femur

The dysplastic and degenerative changes that develop as a result of coxa valga and fetal anteversion are named proximal femur abnormalities. Spastic hip flexors and adductors force the femur head into the posterolateral acetabular labrum. The superior margin and the capsule of the acetabulum cause focal deformation of the femural head (Bagg et al., 1993). All these events can cause cartilage erosion of the femoral head at the lateral acetabular margin and result in pain. The epiphysis becomes wedge-like and is displaced superolaterally (Black and Griffin, 1997; Selva et al., 1998).

TABLE 21.2 Comparison of spastic hip dysplasia and developmental hip dysplasia.

	Spastic hip dysplasia	Developmental hip dysplasia
Findings at birth	The hip is usually normal	The hip is usually abnormal
Age risk	Usually normal the first year after birth and noticed after 2 yrs	Noticed in the first year after birth.
Results	Radiography needed in many cases	Physical examination is adequate in many cases
Etiology	The spastic muscles force the femur out of the normal acetabulum and cause pelvic obliqueness	Mechanical factors such as ligament laxity, abnormal acetabular development
Childhood progression	Usually progressive subluxation	Rarely progressive subluxation
Acetabular problem	Usually posterosuperior	Usually anterior

A study using three-dimensional computed tomography (CT) has found serious deformities of the femural head in all non-ambulatory patients from mild medial straightening to wedge-shaped defects. The large trochanter preserves the normal ratios in many hips while the small trochanter becomes enlarged. Many findings indicate that femoral anteversion is increased in spastic hip dysplasia. The coxa valga caused by the anteversion and the neck-shaft angle may be at high degrees in some children. Normal anteversion is seen at birth in children with spastic hip dysplasia but the expected decrease in anteversion in the early childhood period is not observed (Cornell, 1995; Park et al., 2014).

Acetabulum Major progress has been made in understanding the acetabular abnormalities in spastic hip dysplasia. Computerized mathematical models indicate that the hip strength is six times higher in a child with spastic hip disease (Brunner et al., 1997). This constant abnormal force leads to the very early appearance of changes. The acetabular index (AI) is normal until the 30th month in the affected child and then becomes significantly increased (Kim and Wenger, 1997). Heinrich et al have evaluated the arthrograms and found that the bone maturation of the acetabulum is delayed due to lateral pelvic cartilage deformation before and during the subluxation. The most significant increase in acetabulum deformation is in the hip with a Migration Index of 52–68%. The acetabular defect is usually posterosuperior. Instability develops as a result of compression by the femur head and is usually one way. In cases with the rare elongation posture, the dislocation and the associated acetabular deficiency is anterior (64). Kim and Wenger analyzed three-dimensional CT images and found that the major acetabular defect normally corresponded to the subluxation or dislocation but there could be exceptions. There is no consensus on whether the acetabulum is actually shallow or normal (Kim and Wenger, 1997).

Hip joint in meningomyelocele

Hip problems develop in 30–50% of children with spina bifida (SB) in the first 2–3 years together with hip instability (subluxation/dislocation) and flexion deformity (Kashiwagi et al., 1996). Hip joint problems are not frequent in children with sacral lesions while the incidence can reach 70% in case of upper lumbar and thoracal involvement (Dias, 2004; Mazur et al., 1989). Hip instability develops due to congenital factors in developmental hip dysplasia but the instability in SB is caused by the weakness of the muscles around the hip, the imbalance in strength between the muscle groups, spine and leg deformities (e.g., the knee, feet), and the fact that the natural walking characteristics of the children have not developed (Dias, 2004; Yorgancioğlu et al., 2005; Czeizel and Dudas, 1992). In the past, it was thought that the children with SB had to walk to improve their general condition and that a stable, non-deformed hip was needed for the walking function. However, hip dislocation has little effect on the child's walking function. The problems around the hip that lead to an unwanted gait usually originate from fixed hip flexion contracture resulting in lumbar lordosis. Another important point is that mobilization of the children over the age of 10 with SB showing marked involvement is easier and more ergonomic with a wheelchair (Guille et al., 2006). Whether hip instability treatment is needed in children with SB at present is controversial. Prevention and treatment of hip dislocation in these patients differs from typical developmental hip dysplasia. The risk/benefit ratio for orthopedic problems of children with SB should be evaluated carefully, especially for surgical treatments. The factors affecting the treatment for hip instability in SB patients in the literature are the child's mobilization potential whether the hip dislocation is bilateral or unilateral (Yorgancioğlu et al., 2005). Surgical intervention can generally have encouraging results in patients with lower level involvement (lower lumbar, sacral) and a walking potential while the outcome can be unsuccessful in patients with high level involvement (thoracal, upper lumbar) who cannot walk. Treatment of hip dislocation should therefore be withheld in patients who cannot be mobilized without support while surgical treatment can be suggested only for unilateral dislocations in patients who can walk (Erol et al., 2005), (Swaroop and Dias, 2009). If there is a sign for the decrease and stabilization of the dislocated hip in young children, open hip reduction, pelvic osteotomies (periacetabular bone interventions; Pemberton or Chiari osteotomy) and femoral osteotomies (proximal femoral bone interventions; femoral varus derotation osteotomy) can be used in various combinations. When fixed flexion contracture has developed in the patient, anterior hip relaxation can be used to release all the soft tissues other than the skin and the neurovascular structures that appear before the hip (Yorgancioğlu et al., 2005; Swaroop and Dias, 2009).

Pelvic obliqueness

Pelvic obliqueness is inadequacy of the horizontal position with the pelvis becoming perpendicular to the spine as related to the frontal plane. The reason for pelvic obliqueness is the separate or combined contracture of each of the muscles extending from the pelvis to the femur, from the spine to the femur, and to the pelvis, and the presence of a long curve including the sacrum. Various degrees of pelvic obliqueness are seen in SB patients (Seitzberg et al., 2007).

Hip pathomechanics in specific orthopedic conditions

Hip osteoarthritis

Osteoarthritis (OA) is derived from the Greek words "bone", "joint" and "inflammation" (Hou et al., 2015). OA is a joint disorder characterized by biochemical and morphological differentiations resulting from imbalance between cartilage construction and destruction of joints, under the influence of many risk factors such as trauma, overuse and genetic predisposition (Jevsevar, 2013). The most common form of arthritis is OA, which is one of the main causes of pain and disability in individuals around the world. (French et al., 2011). Osteoarthritis is a major reason of functional disability. Yielding the support of the cartilage may lead to the functional disability.

The risk factors affecting the development and progression of osteoarthritis can be divided into two groups (Felson, 2013; Creaby et al., 2013; Berenbaum, 2013): a) Non-mechanical and non-changeable factors such as age, obesity, sex, genetic characteristics; b) mechanical factors such as muscular strength inability, abnormal biomechanics, gait and movement defect.

Mechanical factors can lead to abnormal joint loading and negative progression of the osteoarthritis process. Although there are publications showing that abnormal loadings have a negative effect on the osteoarthritis process (Creaby et al., 2013; Robbins et al., 2013) publications showing abnormal joint loading and/or abnormal joint biomechanics affect hip osteoarthritis process are strongly needed.

When three-dimensional motion analysis studies are examined in patients with hip OA, it has been shown that movements in the sagital and frontal plane are reduced, functional joint range of motion was restricted, the response to joint loading became weaker and all the factors caused walking pathologies (Eitzen et al., 2012; Meyer et al., 2015). Decrease in the strength of a joint against loading which is an effect that accelerates the osteoarthritis process, is often associated with a reduction in the strength of muscle and soft touch that surrounds the joint. "Does osteoarthritis reduce the strength of muscle and soft tissue?" or "Does the reduction of soft tissue and muscle strength reduce the strength of the joint against loading?" are not unknown. Weak hip load in hip OA and weakness in hip circumference muscles were found to be related (Arokoski et al., 2002). Principal component analysis (PCA) has frequently been performed following total hip endoprostheses (Whatling et al., 2013), has not been used except in pre-surgery which means severe hip osteoarthritis (Meyer et al., 2015). Meyer et al. showed with PCA that there is a significant reduction in the transmission of information related to movement in hip osteoarthritis and it ruins the mechanism of gait. Meyer et al. (2015) showed that, decreased hip flexion moment and maximal hip extension in sagittal plane lead pathological gait patterns in patients with hip OA.

Patients with hip OA tend to restrict functional movement of the hip, especially by taking the hip into extension, reduce the load on the hip joint because of pain, hip flexor muscle contracture, and/or muscle weakness of the hip circumference (Hurwitz et al., 1997). As a result of the decrease in the muscle strength of the abductor of hip OA patients, deviation occurs in the moments of rotation and abduction of the hip (Meyer et al., 2015). A decrease occurs in the internal rotation of hip especially in midstance phase due to the inadequacy of the gluteus medius muscle. Gluteus medius muscle contributes to hip internal rotation when the hip is flexed. Gluteus medius insufficiency reduces both hip internal rotation and hip abductor moment (Moore et al., 2014). Decrease in hip abductor moment causes decrease in hip adductor moment and increase in lateral flexion movement.

It is important to reflect these changes which occur in patients with hip OA into rehabilitation protocols.

Exercises protecting hip mechanics, increasing joint limit of movement, improving muscular strength and soft tissue tensile strength must be added to the prescription for patients. Furthermore, studies that are examined hip mechanics of hip OA patients in different activities such as going down ladder, ascending a ladde, take off, running and landing apart from walking are needed.

Femoroacetabular impingement (FAI)

Femoroacetabular impingement (FAI) syndrome is common in the young and middle-age group and is considered as a preliminary factor in hip osteoarthritis. There are three types: Excessive acetabular covering (pincer type), nonspherical femoral head (cam type), and mix type (Wisniewski and Grogg, 2006).

The most characteristic symptom of femoroacetabular impingement is the pain in the groin. This may be accompanied by a decrease in chronic pain and range of motion in flexion and internal rotation. It occurs as a result of friction in the hip joint caused by abnormal contact between the rim of the acetabulum and the femoral head. Over time, the repetitive contact can cause damage to the articular or labral cartilage, which may lead to degenerative joint disease (Wisniewski and Grogg, 2006; Rutherford et al., 2018). Biomechanical studies related to FAI using EMG showed that there was an increase in the activation of gluteus maximus and medial hamstring activation was greater than lateral hamstring (Rutherford et al., 2018). This can be interpreted as a major overload in the medial part of the knee and medial stabilization adversely affected in the medial part of the knee. As in the knee osteoarthritis, the increase in activity in the medial Hamstring causes the toe-in walk. This toe-in walk pattern may be a gait disorder developed by FAI patients to provide stabilization of the hips and/or knees. The gait disorders in FAI are sex-dependent. Individual-specific changes are seen in males, while there are specific variations of lower extremity type in females (Lewis et al., 2018). This suggests that there is more variety in gait disturbances in male with FAI.

The peak extension and abduction strength decrease bilaterally, anterior pelvic tilt increases, posterior pelvic tilt decreases and all these cause hip angle curve in the sagittal plan in male with FAI. The increase in peak hip extension and hip abduction is accompanied by an increase in peak hip adduction in female. In addition, anterior pelvic tilt significantly increases during squatting, stair climbing activities (Lewis et al., 2018; Diamond et al., 2017).

Likewise, there are changes in the frontal plan according to sex. There is a significant reduction which negatively affects the gait speed in the abduction moment in painful hip. The increase in the hip adduction moment of female with FAI indirectly leads to a reduction of the abduction moment (Rutherford et al., 2018; Lewis et al., 2018; Diamond et al., 2017). Increased anterior pelvic tilt which is developed or exist and hip adduction moment leads to impingement. This may trigger pain during squatting, stair climbing and running, even if it is not during walking.

Proximal femur fractures

Proximal femur fractures are the most common type of fracture that can cause death, especially in the geriatric population (Hahnhaussen et al., 2011). Proximal femur fractures are treated with surgery. Proximal femur fractures are treated by using IM nail or an extramedullary sliding hip screw (SHS) or hip arthroplasty methods depending on the condition of the patient or the choice of the surgeon. Studies analyzing how IM nail or SHS with fixation affect the mechanism of walking or other activities on biomechanical models which means experimental models (Fleps et al., 2018; Olson et al., 2015). These studies emphasize the importance of rotational stability in addition to the valgus-varus moment. It has been showed that the hips could heal with more than 5° varus collapses with shortening more than 5 mm in a multi-centered study (Hahnhaussen et al., 2011). It is emphasized that the amount of collapse and shortening is excessive and the quality of life and functional level of the patients are affected more negatively in this study which does not include a biomechanical review (Zlowodzki et al., 2008).

Hip endoprostheses

There are many biomechanical studies on arthroplasties, which are frequently used in arthroplasty in hips fractures and osteoarthritis. Hip endoprostheses are applied totally or partially, the clinical condition of the patient, the age and the surgeon decide which of these options to be implemented. After hip endoprosthetic surgeons, patients tend to transfer their body weights towards the non-surgical side. There is a 24% decrease in the ground reaction force in addition to the decrease in the functional joint movement of the extremity which has had an operation. It has been shown that the ground reaction force increased 6% and 11%, respectively, in hip and knee flexion moments on the surgical side, increased by 4% and 8%, in hip and knee flexion moments on the non-surgical side, respectively after hip endoprosthesis (Lewis et al., 2018; Diamond et al., 2017). It has been showed that hip and knee flexion moments decreased by 24% and 32%, respectively in the measurements made before surgery in cases with severe hip and it was reported to be 19% and 20% in mild and moderate hip OA, respectively (Abujaber et al., 2015; Eitzen et al., 2014). Studies underline that patients with asymmetrical movement patterns may be surgical candidates (Eitzen et al., 2014; Caplan et al., 2014).

Whether a hybrid or a cemented endoprosthesis should be used, the answer is not surprising: There was no difference in femoral offset or leg length between both surgical techniques. Although the authors consider that both are appropriate methods for natural hip mechanics, they indicated that long-term follow-up is needed (Le Duff et al., 2016).

Longworth et al. (2018) found that deformed hip and knee biomechanics and their coordinated movements improve significantly after surgery in patients with severe hip osteoarthritis. Nevertheless, when compared with healthy controls, the data are not normalized. According to the authors' results, there may be a relationship between the amount of sagittal plan movement and the amount and duration of loading on the non-surgical side. For this reason, the gait speed of individuals with hip endoprosthesis slowed down (Longworth et al., 2018). Although the functional level improves after hip endoprosthesis, it is known that range of motion of the hip and external moments decrease. Gait anomalies are also seen in addition to the development at gait distance and gait duration (Le Duff et al., 2016; Longworth et al., 2018; Foucher and Freels, 2015). Studies emphasized advanced preoperative abductor strength is related to greater postoperative hip adduction and moments of external rotation, moments of lower abduction (Le Duff et al., 2016; Longworth et al., 2018; Foucher and Freels, 2015).

Finally, there are debates about how lateral and anterior surgical interventions affect abductor function compared to posterior interventions (Berstock et al., 2015; Fleps et al., 2018; Queen et al., 2014; Judge et al., 2013). Although posterior interventions are thought to affect abductor function worse, because of the placement of gluteal muscles, the results of the studies contradict each other. Abnormal movement patterns developing in the pelvis after all hip pathologies and surgeons, femoral anteversion, varus-valgus stress of the knee should be assessed very well and rehabilitation approaches should be designed according to this. Nevertheless, it should not be forgotten that each patient has its own mechanism, learned behaviors, and joint proprioceptor number/level.

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Chapter 22

Kinesiology of the knee joint

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Introduction

Knee joint is the largest joint in human body. Although it primarily functions as a hinge joint, the knee's motion is polycentric including a combination of rolling and sliding. The complexity of the knee joint movements is achieved by the interaction between static stability (bony congruence, ligaments, meniscus, cartilage, capsule and capsular ligaments) and active stability (muscle forces). The static stability of the knee is primarily based on soft tissue restraints rather than on its bony congruence as the articulation surfaces of the femur and tibia are not a close fit to one another. Thus, injuries of the soft tissues of the knee joints are more common as a result of greater stress placed on them during daily and athletic activities.

The knee joint consists of two distinctly separate joints; tibiofemoral joint and patellofemoral joint. The main functions of the joint complex are: 1) to transmit the forces from the femur to tibia, absorb and redistribute the stresses during activities, 2) to allow locomotion with minimum energy requirement.

Tibiofemoral joint

At the distal end of the femur, there are two large convex surfaces: the medial and lateral condyles (Table 22.1). The femoral condyles are cam-shaped in lateral view. Compared to the lateral condyle the medial condyle has a larger radius of curvature. The condyles are separated by the intercondylar notch in the posterior and the trochlear groove in the anterior. The anterior articular surfaces of the medial and lateral condyles provide articulation of the patella. The intercondylar notch provides attachments for the anterior and posterior cruciate ligaments. The condyles also provide attachment sides for collateral ligaments. Articular cartilage covers the surface of the femoral condyles. The femoral condyles articulate with the corresponding tibial condyles (Fig. 22.1).

The superior surfaces of the tibial condyles are nearly flat, so they are also called as the tibial plateau. The articular surfaces of the tibia condyles are separated by the intercondylar eminence, and anterior and posterior intercondylar fossa. The cruciate ligaments and the menisci have an attachment along the intercondylar regions. The prominent tibial tuberosity which serves as the distal attachment for the quadriceps femoris is in the anterior surface of the proximal tibia. The articular surfaces of the medial and lateral tibial plateaus are different. Comparing to lateral plateau, larger articular surfaces of the medial plateau diminishes the stress applied to the medial tibial plateau. Thus, medial tibial plateau carries more loads in upright stance position.

Normal alignment versus malalignment of the tibiofemoral joint

Frontal plane

The differences in articulation surfaces of the tibiofemoral joint cause different loading pattern over tibial plateau depending on the activity. Under normal conditions, the load on the medial side is greater than lateral side. The medial femoral condyle and medial tibial plateau are more elongated, or ovoid, than in the lateral compartment. The articular surface of the medial tibial plateau is concave, whereas the lateral plateau has an anteroposterior convexity. The articular surfaces of the tibia are nearly horizontal, and the shaft of the femur descends medially and is oriented as oblique due to 125° of inclination angle of the proximal femur. Thus, normal frontal alignment of the tibiofemoral joint shows slight valgus in that 170° to 175° angle is formed on the lateral side of the joint (Fig. 22.2) (Chao et al., 1994; Oatis 2009; Neumann, 2013). This valgus angle has a crucial role during locomotion as it leads to less lateral shift of the body to keep the center of the mass of the body on the base of support.

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TABLE 22.1 Lateral condyles versus medial condyles.

Medial femoral condyle	Lateral femoral condyle
1. Extends farther distally 2. Larger in anteroposterior and proximal-distal dimension (contributes valgus) 3. Greater contact area 4. Align with the tibia 5. Preeminence for compression load (sagital plane)	1. Flatter distally (larger radius curvature) 2. Shorter articular surface for tibia 3. The anterior surface of the lateral condyle extends more anteriorly (prevent lateral patellar dislocation) 4. Align with the femur 5. Preeminence for tensile load (transverse-frontal plane)
Medial tibial condyle	**Lateral tibial condyle**
1. Larger articular surface (bears more force) 2. Articular surface is flat to slightly concave 3. Longer in anteroposterior direction	1. Articular surface is flat to slightly convex (not fit to femoral condyle)

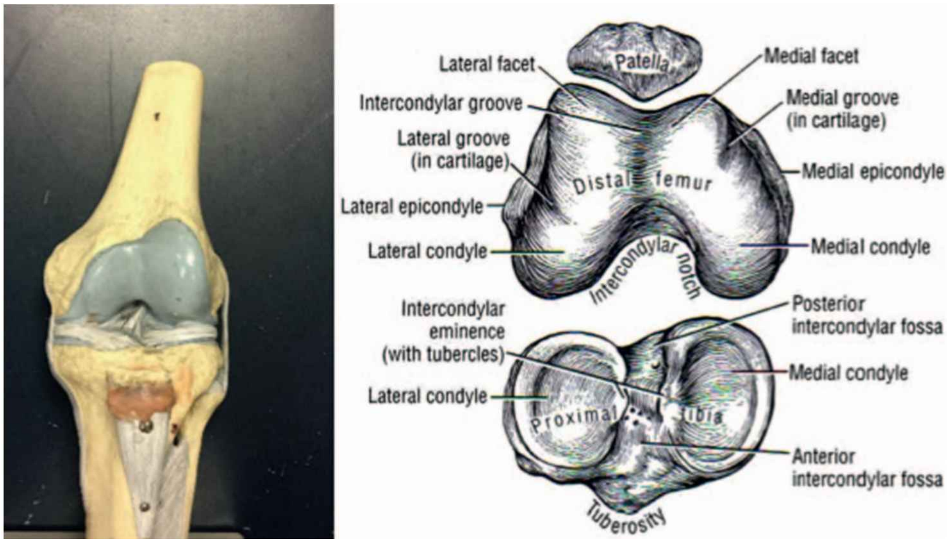

FIGURE 22.1 Articular surface of the distal femur and the proximal tibia.

In genu varum or varus malalignment (deviation of the knee joint away from the midline of the body >180°) the medial compartment carries most of the load. In genu valgum or valgus malalignment (deviation of the knee joint towards the midline of the body) the lateral compartment carries more load (Oatis, 2009; Neumann, 2013). Since the weight-bearing axis is no longer passing through the knee joint center, these malalignments place excessive stress on the medial or lateral side.

Sagittal plane

In erect standing position, the angle between femur and the tibia is 180° in sagital plane. When the angulation of the tibiofemoral joint is beyond neutral or greater than 5° of extension, it is called genu recurvatum (hyperextension deformity of the knee) (Fig. 22.3) (Loudon et al., 1998). The ground reaction force line shifts anterior to the center of knee joint. The end-range of the extension movement of the knee is not limited by bony contact. The hyperextension is controlled by soft-tissue structures.

During weight-bearing knee extension, the femur does not continue to roll anteriorly but tilts forward due to hyperextension, creating anterior compression between the femur and tibia. A hyperextension with normal femoral internal rotation leads excessive stress on the posterolateral corner of the knee joint and the anterior cruciate ligament (Loudon et al., 1996, 1998). Thus, genu recurvatum is thought to be one of the risk factors for anterior cruciate ligament (ACL) injuries in athletes.

Tibiofemoral joint motions

The variation of the articular surfaces of the tibiofemoral joint also contributes to the complex 3-dimensional motion. With computerized motion analysis, 6 degrees of freedom for tibiofemoral joint can be discerned. These are including three rotations (internal-external, abduction-adduction,

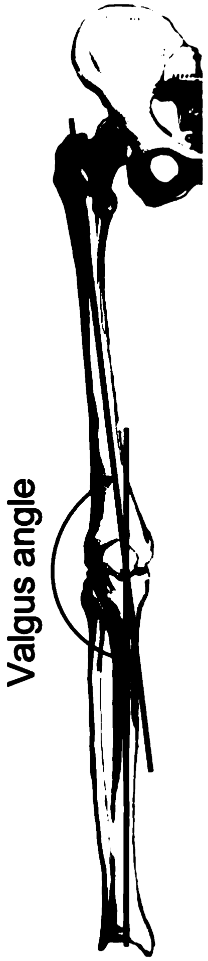

FIGURE 22.2 Valgus angle of the normal alignment. Q angle is calculated as 180°- knee valgus angle.

flexion- extension) and three translations (anterior-posterior drawer, medial-lateral shift, and compression-distraction) (Marans et al., 1989; Lafortune et al., 1992; Ramsey and Wretenberg, 1999). In medio-lateral axis, flexion and extension with medial-lateral shift; in antero-posterior axis, abduction-adduction with anteroposterior drawer; in supero-inferior axis, internal-external rotation with distraction-compression occurs.

During weight-bearing knee flexion from full extension to 90º, femur rolls posteriorly and translates anteriorly and externally rotates on the articular surface of the tibia. The external rotation of the femur reaches approximately 20º and femoral abduction occurs 5º. On the opposite, anterior rolls, posterior translation, and internal rotation occurs when knee extends from 90º flexion to full extension (Patel et al., 2004). When compared to medial condyle, lateral condyle of the femur slides more posteriorly during knee flexion but the translation of both condyles are very small. The medial condyle rolling-to- translation ratio is 1:1, whereas the lateral condyle ratio is 1:4 (Shapeero et al., 1988).

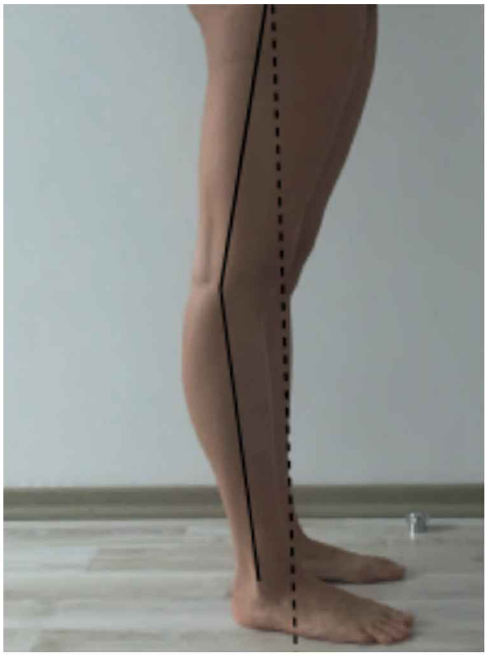

FIGURE 22.3 Genu recurvatum. The ground reaction force line shifts anterior to the center of knee joint.

During non-weight-bearing knee flexion from full extension, tibia rolls posteriorly, translates posteriorly and rotates internally (Fig. 22.4). On the opposite, it rolls and translates anteriorly and rotates externally.

In general, the abductor-adductor motion is approximately 5°, internal and external rotation are approximately 35°, and flexion and extension motions are 150°. Antero-posterior slide is maximal between 30° and 90° of knee flexion (Nigg and Herzog, 2007; Oatis, 2009).

Screw-home (locking) mechanism

During the last 20° of knee extension in non-weight bearing position, the tibia rotates externally and locks into extension (Levens et al., 1948). This motion is called screw-home mechanism which is described as being generated by asymmetry between the femoral condyles (Frankel and Nordin, 1980; Piazza and Cavanagh, 2000). As the medial femoral condyle is approximately 1.7 cm longer and the articular surface extends farther anteriorly than the lateral condyle, tibia rotates externally during the terminal knee extension (Fig. 22.5). The lateral pull of quadriceps muscle and passive tension of ACL have also contributed this mechanism.

The unlocking mechanism is achieved by the popliteus muscle. Popliteus muscle unlocks the knee joint internally rotating the tibia (non-weight bearing) (Mann and Hagy, 1977). Screw home is the characteristic of healthy knee motion and its absence is often described as indicative of instability or joint damage such as meniscus tears

(Frankel and Nordin, 1980; Kim et al., 2015). Because of its clinical importance, the screw-home mechanics is carefully checked after total knee replacements (Karrholm et al., 1994; Piazza and Cavanagh, 2000).

Patellofemoral joint

Patellofemoral joint is one of the incongruent joints that is formed by the articulation between patellar articulation surface and the femoral trochlear groove.

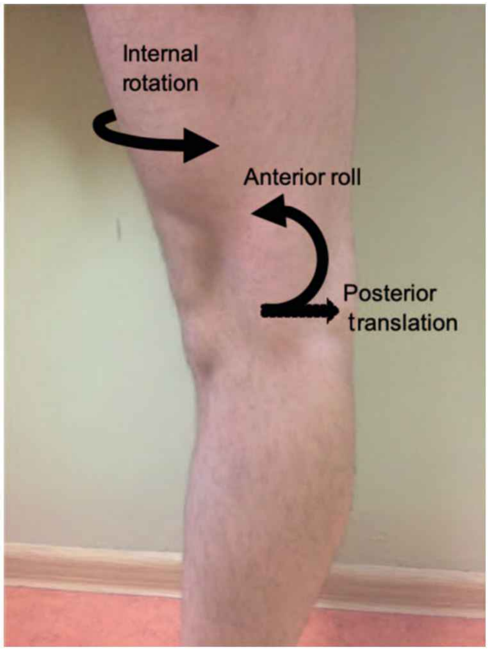

FIGURE 22.4 Osteokinematics of the tibiofemoral joint. Femoral- on-tibial extension (weight-bearing). The femur rolls anteriorly, translates posteriorly, and rotates internally when knee extends from flexion to full extension.

Patella

Patella is the largest sesamoid bone in the human body. It has a triangular shape with apex pointing distally. The posterior surface consists of 2 major concave facets (medial and lateral) and odd facet. The odd facet is adjacent to the medial facet. The sizes of the facets may vary depending on the patella type. In type 1 patella, the size of medial and lateral facets are similar. In type 2 (the most common), lateral facet is slightly larger than the medial facet. In type 3, larger lateral facet exists with a very small vertical medial facet. It has been thought that individuals who have type 3 patella are vulnerable to patellar dislocations and chondromalacia patella (Stefancin and Parker, 2007).

The medial and lateral facets articulate with the femoral groove when the knee is flexed. The odd facet only articulates with the medial femoral condyle in deep knee flexion. The extra-articular part (distal part) of the patella attaches to the patellar tendon (Fig. 22.6). The articular surface of the patella is covered with articular cartilage up to 4–5 mm thick.

The primary function of the patella is to improve the pulley effect by increasing the moment arm distance from the extensor mechanism to the instant center of motion of the knee (Hungerford and Barry, 1979). In addition, the patella centralizes the divergent pull from the four muscles of the quadriceps and transmitting the total forces to the patella tendon (Hungerford and Barry, 1979, Schindler and Scott, 2011). Without patella, the quadriceps getting longer and unable to shorten effectively during full extension. In this scenario, the quadriceps must generate greater force to produce a moment.

Trochlear groove

Trochlear groove has a crucial role when the patella engages it at 15°–20° knee flexion (Fig. 22.7).

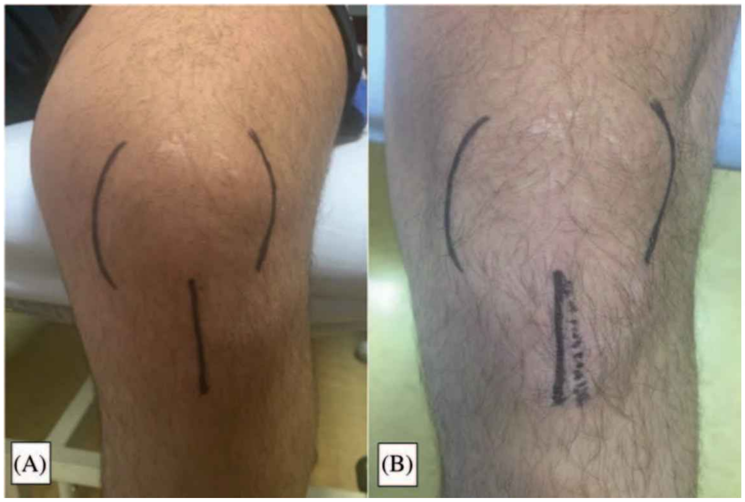

FIGURE 22.5 Screw home-mechanism.

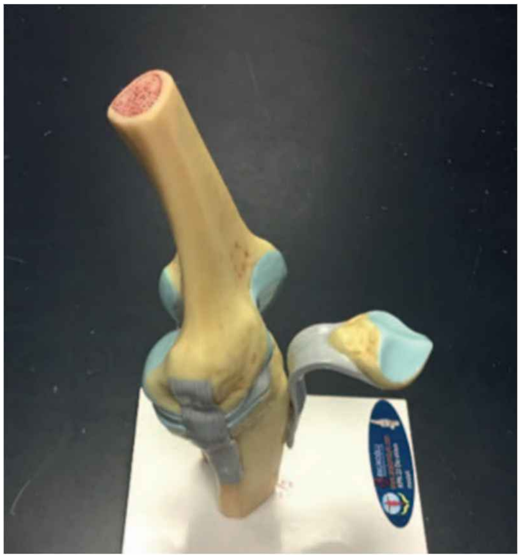

FIGURE 22.6 Patella and patellar tendon.

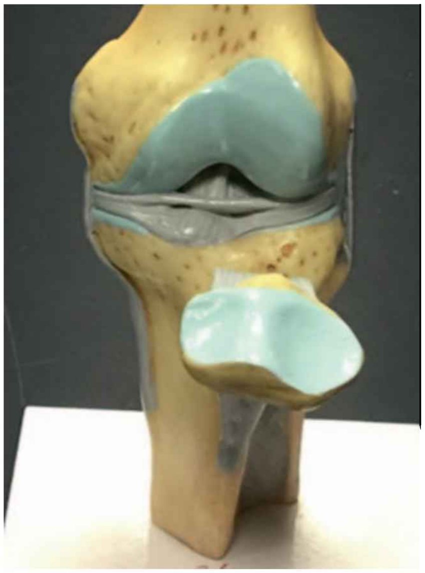

FIGURE 22.7 Trochlear groove.

The primary restraint against the lateral translation of the patella is the slope of the lateral wall of the trochlea. Therefore, trochlear dysplasia is one of the risk factors for patellar instability. In early knee flexion, lateral femoral condylar slope and height enhances the patellar engagement and help to decrease the rates of lateral subluxation of the patella (Amis, 2007; Davies-Tuck et al., 2008).

Normal alignment versus malalignment of the patellofemoral joint

Sulcus angle is defined by the lines joining the highest points of the medial and lateral condyles and the lowest point of the intercondylar sulcus which is the depth of the sulcus over the femoral surface (Fig. 22.8) (Kujala et al., 1989; Powers, 2000).

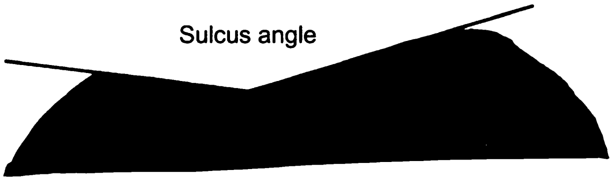

FIGURE 22.8 Sulcus angle.

The sulcus angle is measured using a Merchant view radiographs (a view of the patellofemoral contact area at 45° of knee flexion) and is associated with trochlear dysplasia (Merchant et al., 1974). The sulcus angle has been shown to be related with the age that is flattest in children and getting deeper through aging. In asymptomatic adult subject, the sulcus angle was reported between 130° and 146° (Merchant, 1991; Dejour et al., 1994; Balcarek et al., 2010) and it was larger (shallower) in individuals with patellar instability (Pfirrmann et al., 2000; Powers, 2000; Balcarek et al., 2010). Balcarek et al. (2010) found gender difference in sulcus angle in individuals with patellar dislocations. Sulcus angle in women (155°) was greater than the men (150°) at 30° of knee flexion.

Merchant's technique is mostly used for measuring the congruence angle (Fig. 22.9). Congruence angle is measured from 45° of flexion. It is made by bisecting the sulcus angle to create a zero-reference line. Then a line is drawn from the lowest point on the patella to the sulcus angle point (Kujala et al., 1989). The angle between the two lines is defined as congruence angle that shows how patella fits on the trochlear groove. The 'normal'' value is -6 ± 11 degrees at 45° of knee flexion in asymptomatic adults (Merchant et al., 1974). Schutzer et al. (1986) reported that a congruence angle greater than 0° at 10° of knee flexion should be abnormal.

Patellar tilt is the rotation of the patella in superior inferior axis. In resting position, the patella positioned slightly lateral tilt. Patellar tilt angle is measured by a line joining the medio-lateral corners of the patella and a horizontal line at 30°of knee flexion (Fig. 22.10) (Grelsamer et al., 1993). Grelsamer et al. (1993) suggested that a tilt angle between 0° and 5° is normal, 5° to 10° is borderline, and an angle greater than 10° is considered as abnormal. The abnormal patellar tilt links to tight lateral patellar retinaculum, insufficient medial ligamentous support or malposition of the tibial tubercle (Merchant, 1991).

Patellar tracking is the transition of the patella medially or laterally. Excessive lateral transition is related to patellofemoral pain syndrome (Witonski and Goraj, 1999). Lateral displacement can be measured by comparing the medial margin of the patella on an axial view to the medial femoral condyle. The lateral displacement more than 1 mm is considered as subluxed (Laurin et al., 1979).

Patella alta is described when the distance between tibia and the patella increased, while patella baja describes the decrease in the distance between tibia and patella. Patella alta increases the patellar translation before the patella engages the trochlea during knee flexion and it was shown that 24% of the patients with patellar instability had patella alta (Dejour et al., 1994). Patella alta also increases the stress on the articular cartilage due to decrease in the contact area for joint loading during knee flexion (Luyckx et al., 2009).

Patellofemoral motion during flexion and extension

Patellar stability is influenced by the geometry of the trochlear groove, the height and the slope of the lateral femoral condyle, dynamic muscle actions, passive soft tissue restraints and the knee flexion angle (Amis, 2007; Feller et al., 2007; Greiwe et al., 2010). The articular geometry of the patellofemoral joint becomes important after the first 20°–30° of knee flexion. This is because the patella does not engage the trochlea until 20° of knee flexion (Amis, 2007).

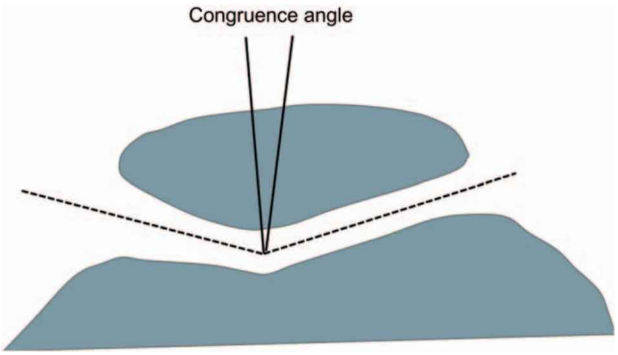

FIGURE 22.9 Congruence angle.

In resting knee full extension position, patella lies above the intercondylar groove with high mobility and it can be easily mobilized in a medio-lateral direction when the quadriceps relaxed. The patella translates medially when the knee flexed to 20°–30° then it translates laterally (Hungerford and Barry, 1979; Grelsamer and Klein, 1998; Powers et al., 1998; Amis et al., 2006) and this motion is described as a C-curve pattern (Hungerford and Barry, 1979). However, this translation minimally occurs during flexion as the patella remains relatively centered on the trochlea and medio-lateral translation difference of the patella was found 6.5 mm between 0° and 90° knee flexion (Amis et al., 2006). Amis et al. (2006) measured patellar tilt angle during knee flexion. In the first 20°of knee flexion, the patella laterally tilts 4°–5°, followed by further lateral tilting up to 7.3° by 90° of knee flexion. The patella glides superiorly and inferiorly on the femur during extension and flexion of the knee, respectively. The total excursion of the patella from full knee extension to full knee flexion is 5 ± 7 cm

Patellofemoral contact area

The location of the patellar contact area shifts from distal to proximal as the knee flexes (Fig. 22.11). The patella is not in contact with the femur in full extension where it lies proximal to the trochlear groove. When the knee begins to flex, lateral facet of the patella contacts with the lateral femoral condyle. At 30° of knee flexion, both sides of the condyles contact with the medial and lateral facets of the patella and the total contact area is approximately 2 cm^2. The area of the contact gradually increases as the knee flexion angle increased and the joint becomes more congruent. The contact area reaches at 6 cm^2 when the knee flexes 90° and the superior portion of the patella contact with the trochlear groove. At full flexion (135° or beyond), only odd facet of the patella contacts the lateral aspect of the medial femoral condyle and the lateral facet of the patella still contacts with the lateral femoral condyle to maintain lateral stability of the patellofemoral joint. The contact area decreases after 90° of knee flexion.

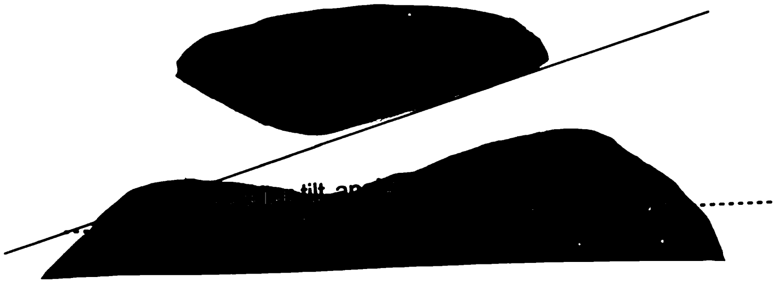

FIGURE 22.10 Patellar tilt angle.

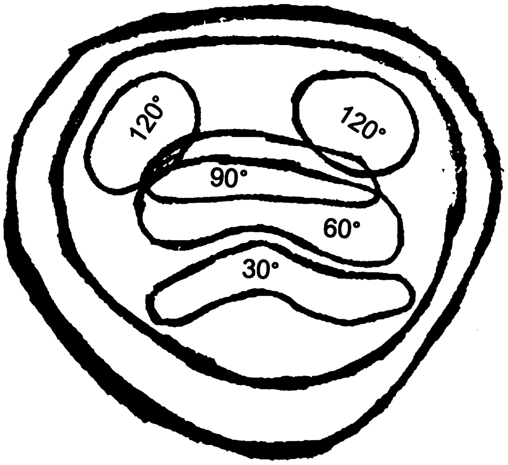

FIGURE 22.11 Patellar contact area.

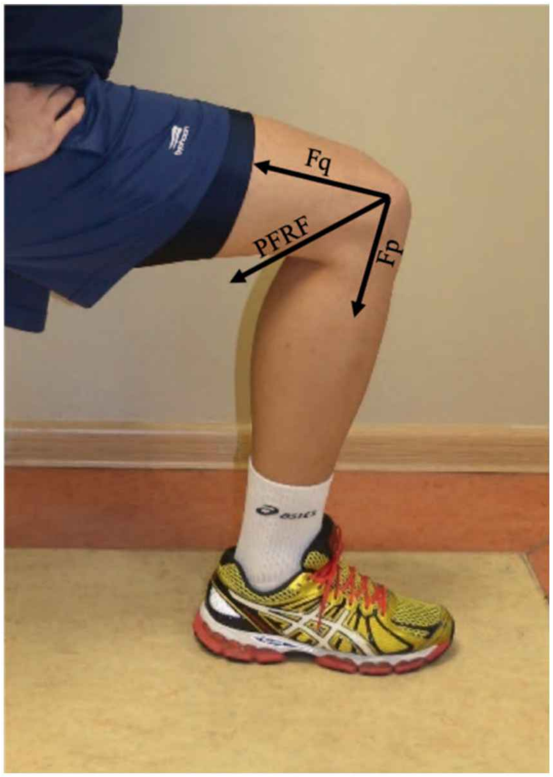

FIGURE 22.12 Patellofemoral reaction force (PFRF). The PFRF is equal to the resultant of the quadriceps tension (Fq) and patellar tendon tension (Fp) and acting perpendicular to the articular surfaces.

Patellofemoral joint reaction force

The patellofemoral reaction force (PFRF) is equal to the resultant of the quadriceps tension and patellar tendon tension and acting perpendicular to the articular surfaces (Fig. 22.12). PFRF increases with increasing knee flexion.

The compressive forces placed on the patellofemoral joint is divided by the patellofemoral joint contact area and referred to patellofemoral joint stress (PFJS) measured as force per unit area (Grelsamer and Klein, 1998).

Patellofemoral joint stress in weight bearing versus non-weight bearing

To quantify PFJS, it is needed to know knee extensor moment, knee flexion angle, PFJ contact area, quadriceps level arm and the relationship between quadriceps force and PFRF. Powers et al. (2014) investigated PFJS during weight-bearing squat exercise and non-weight-bearing knee extension exercise between 0° and 90° in asymptomatic subjects. They found that PFJS was greatest at 90° of knee flexion (12 MPa) during squat exercise and it decreased as the knee extended. On the other hand, PFJS was lowest at 90° of knee flexion during non-weight-bearing knee extension and it increased as the knee extension, it was maximum at 0° (8.4 MPa). They suggested that performing the squat exercise from 0° to 45° of knee flexion and the knee extension exercise from 45° to 90° of knee flexion would keep PFJS to a minimum (below 4 MPa) for strengthening quadriceps in the early phase of patellofemoral disorders' rehabilitation.

Muscular actions

The muscle groups having a role in knee joint are categorized here as two groups: knee extensors and knee flexors.

The knee extensors

The quadriceps femoris is the primary extensor of the knee joints. It is composed of four separate heads, consisting of rectus femoris, vastus lateralis, vastus intermedius and vastus medialis, each of them has a different role in knee joints movements (Fig. 22.13). Vastus group produces 80% of the total extension torque while the rectus femoris produces 20%. All heads of the quadriceps femoris form the quadriceps tendon which attaches to the base of the patella. The quadriceps tendon continues distally as the patellar tendon that is attached to the tibial tuberosity.

The proximal attachment of the rectus femoris to the anterior inferior iliac spine makes it act as a hip flexor and knee extensor. Rectus femoris inserts into the anterior portion of the superior aspect of the patella with the superficial fibers continuing over the patella and ending in the patellar tendon.

Vastus medialis versus vastus lateralis

The vastus medialis and lateralis have a potential to pull patella medially or laterally since their acting line away

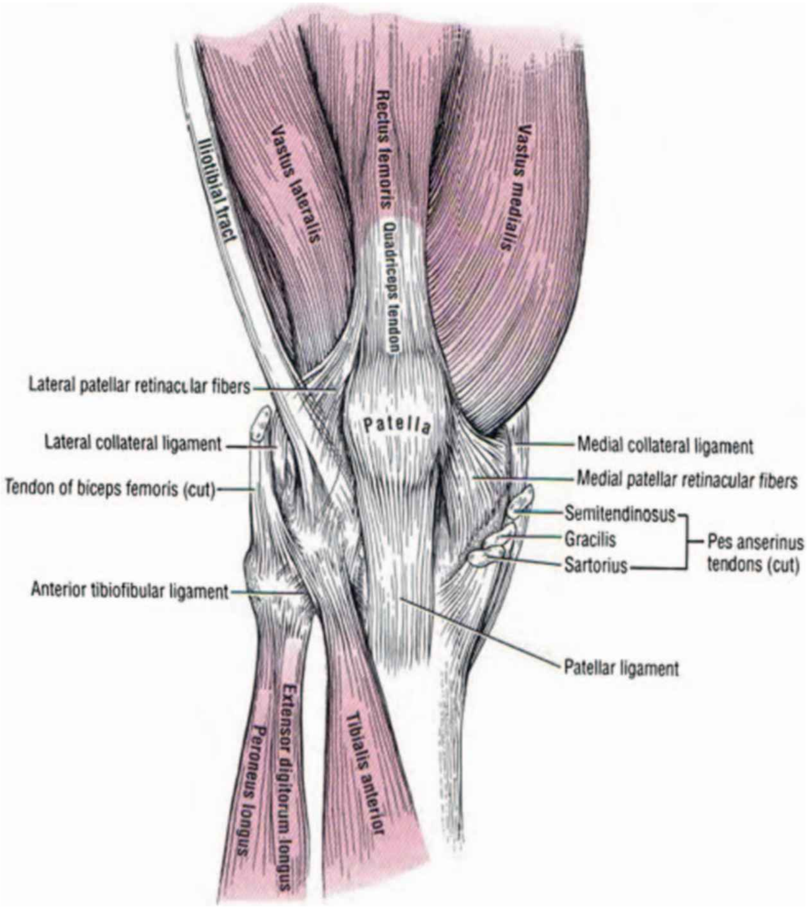
Iliotibial tract
Vastus lateralis
Rectus femoris
Quadriceps tendon
Vastus medialis
Lateral patellar retinacular fibers
Patella
Lateral collateral ligament
Tendon of biceps femoris (cut)
Medial collateral ligament
Medial patellar retinacular fibers
Semitendinosus
Gracilis
Sartorius
Pes anserinus tendons (cut)
Anterior tibiofibular ligament
Patellar ligament
Extensor digitorum longus
Peroneus longus
Tibialis anterior

FIGURE 22.13 Anterior view of the knee joint. Quadriceps muscle consist of vastus medialis, vastus intermedius, rectus femoris and vastus lateralis.

from the long axis of the femur. In addition, they could also pull the patella posteriorly on the anterior aspect of the trochlea when the knee is close to full extension (Farahmand et al., 1998).

The vastus medialis consists of two distinct fiber directions. The more distal oblique fiber, vastus medialis obliquus (VMO), attaches to the patella at 50°−55°. The more longitudinal fibers, vastus medialis longus, approach the patella at 15°−18°. The vastus medialis is approximately 30% of the overall cross-sectional area of the quadriceps femoris and it contributes 10−12% of the total knee extension (Farahmand et al., 1998; Zhang et al., 2003). The most important role of the VMO is stabilize patella during knee extension since it is the only muscle stabilizes the patella medially. Patellar lateral stability was found lowest when the VMO relaxed at 20° of knee flexion in the intact cadaveric knee (Senavongse et al., 2003; Senavongse and Amis, 2005). However, if trochlea is normal, VMO inactivity could not enough to sublux patella laterally. Vastus lateralis is the largest of the quadriceps muscles and contributes 40% of the extension strength of the knee and attaches to the patella at 12°−15°.

Vastus intermedius is the deepest muscle of the quadriceps femoris located under the rectus femoris. Like other vastii muscles, the primer function of the vastus intermedius is knee extension. Although rectus femoris and vastus intermedius located centrally on the femur, lateral deviation of the femur against tibia causes the rectus femoris and vastus intermedius pull patella laterally during leg extension (Oatis, 2009).

Function of the quadriceps femoris

The quadriceps femoris can perform multiple function at the knee with contracts isometrically, concentrically and eccentrically. Its isometric action is used during stabilizing the knee joint, concentric action of this muscle accelerated the tibia or the femur into extension. This is important during running and jumping or standing from a sitting position. The eccentric function of the quadriceps femoris decelerates the knee flexion (controls the rate of the descent of the body's center of mass) to protect the knee joint against the impact of the loading. This protection is crucial during landing from a jump and running.

During gait cycle, the quadriceps involved in both stance and swing phases (Nicola and Jewison, 2012), but during stance phase it only controls first phase of knee extension during the response to loading since quadriceps activity is not efficient when the knee near full extension (Brunner and Rutz, 2013). During early swing phase, rectus femoris eccentrically contracts to control knee flexion which is contributed by the hamstrings. Rectus femoris also contributes hip flexion during swing phase as it is a bi-articular muscle. Quadriceps extend the knee to 0°–20° of full extension during late swing phase when the forward propulsion of the body is at its maximum (Nicola and Jewison, 2012). Adequate knee extension at the terminal swing is crucial to achieving efficient heel contact (Brunner and Rutz, 2013).

Quadriceps angle

The quadriceps (Q) angle is that angle formed between the vectors for the combined pull of the quadriceps femoris muscle and the patellar tendon (Schulthies et al., 1995). The Q angle is defined by a line from anterior superior iliac spine to the center of the patella and from the center of the patella to middle of the anterior tibial tuberosity (Livingston, 1998). Q angle greater than 15°–20° is thought to be related with the lower extremity injuries as lateral pull of the quadriceps increases with abnormal extensor mechanism (Messier et al., 1991; Livingston, 1998; Rauh et al., 2007). However, the studies failed to document the relationship between increased Q angle (static measure) and patellofemoral pain syndrome (Powers, 2003; Herrington and Nester, 2004). Therefore, Powers et al. (Powers, 2003) suggested using "dynamic Q angle" in activity analysis since the patients demonstrated altered lower extremity mechanics (increased femoral adduction and/or internal rotation) during dynamic activities which can affect the Q angle. Stair descending and landing from a jump activity are mostly used for evaluating dynamic Q angle. It has been reported that individuals with patellofemoral pain have increased dynamic Q angle during stair descent compared with healthy controls. The increase in Q angle relates to increase in contact pressures applied on the patella (Chen et al., 2010). Huberti and Hayes (1984) found 4.5% increase in peak contact pressure on the lateral aspect of the patellofemoral joint when he Q angle 10% increased.

The Q angle < 10° provides the most efficient line for the pull of the quadriceps (Byl et al., 2000). Thus, quadriceps force generation capacity may decrease in individuals whose Q angle is greater than 10°.

Women versus male

Women display larger Q angles compared to men but the reasons for this gender difference are unclear (Horton and Hall, 1989; Woodland and Francis, 1992; Guerra et al., 1994; Hahn and Foldspang, 1997). Larger pelvic width (Horton and Hall, 1989; Ando et al., 1993; Livingston, 1998), greater pelvic width to femur length ratio (Pantano et al., 2005), femoral anteversion (Nguyen and Shultz, 2007) and tibiofemoral angle (Nguyen and Shultz, 2007) has been thought to result in larger Q angles in females.

Supine versus standing

Q angle tents to decrease about 0.2°–1.3° from standing to supine where patella superiorly and laterally moved with quadriceps contraction to quadriceps relaxed condition in supine (Woodland and Francis, 1992; Guerra et al., 1994).

The knee flexors

The hamstrings muscles are the primary flexors of the knee joint (Table 22.2). But, gastrocnemius, popliteus, sartorius and gracilis muscles also contribute to knee flexion. The hamstrings consist of biceps femoris (long and short head), semitendinosus and semimembranosus (medial hamstrings) (Fig. 22.14).

Hamstrings biomechanics

During the gait cycle, the hamstring muscles work together to both extend the hip and flex the knee. During the swing phase of the gait cycle, the hamstrings coordinate extension at the hip and control extension of the knee (Koulouris and Connell, 2005). The passive tension of the hamstrings also controls the hip flexion during late swing phase where the forward swing of the thigh

TABLE 22.2 The hamstring muscles origin and insertion.

Hamstring muscles					
Semitendinosus		**Semimembranous**		**Biceps femoris**	
Origo	Ischial tuberosity	Origo	Ischial tuberosity	Origo	Long head: Ischial tuberosity Short head: Linea aspera
Insertio	Medial condyle of the tibia	Insertio	Medial condyle of the tibia, MCL, medial meniscus, oblique popliteal lig., popliteus	Insertio	Head of fibula

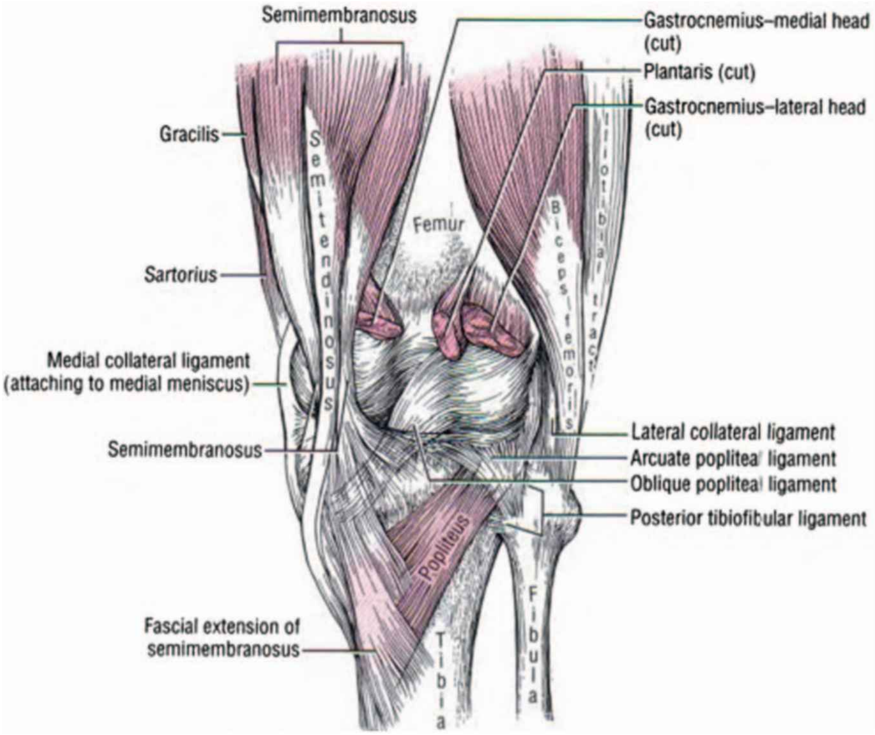
Semimembranosus
Gastrocnemius–medial head (cut)
Plantaris (cut)
Gastrocnemius–lateral head (cut)
Gracilis
Semitendinosus
Iliotibial tract
Femur
Biceps femoris
Sartorius
Medial collateral ligament (attaching to medial meniscus)
Semimembranosus
Lateral collateral ligament
Arcuate popliteal ligament
Oblique popliteal ligament
Posterior tibiofibular ligament
Popliteus
Fascial extension of semimembranosus
Tibia
Fibula

FIGURE 22.14 Posterior view of the knee joint. Hamstring muscles consist of semitendinosus, semimembranous and biceps femoris with short and long head. Gastrocnemius and popliteus, sartorius and gracilis also contribute knee flexion.

happens. At the heel strike, the hamstrings are their maximum length and contracts eccentrically which make them vulnerable to the injury (Thelen et al., 2005). In addition, due to obliquity of the biceps femoris and semitendinosus, the hamstrings have a role on internal and external rotation of the leg when the knee is in a flexed position.

The hamstring muscles contribute the stabilization of the posterolateral and posteromedial corners of the knee joint. Biceps femoris insert iliotibial tract, posterior capsule and lateral collateral ligaments, and when the knee in flexed position, biceps femoris helps lateral collateral ligament to knee its tension to resist varus loads (Marshall et al., 1972). Semimembranosus involves in the posteromedial corner of the knee joint. Its attachment on the posterior oblique ligament has an important role on the stability of the posteromedial corner during knee motions (Tibor et al., 2011).

The hamstrings have a crucial role in aspect of ACL injuries as they are one of the primary active restraints for tibial anterior translation during weight-bearing activities (Renström et al., 1986). Renstrom et al. (1986) demonstrated that the line of pull of the hamstrings as being parallel to and protective of the ACL at knee flexion angles greater than 30°. Quadriceps contraction, on the other hand, lead anterior tibial translation and quadriceps dominancy is thought to be a risk factor for ACL injuries in athletes (Li et al., 1999; Hewett et al., 2013). Thus, co-contraction of the hamstrings with quadriceps is recommended for ACL injury prevention and rehabilitation (Hewett et al., 2013).

Pes anserinus

Sartorius, gracilis and the semitendinosus tendons attach the same area of the medial condyle of the tibia and form pes anserinus (Fig. 22.15). The pes anserinus muscles are internal rotators of the knee joint. However, the most important role of this muscle group is medial dynamic stabilization of the knee joint against valgus stress with the help of medial collateral ligament (MCL).

Popliteus

Popliteus is a very small muscle that originates from the lateral femoral condyle, run oblique and attaches posterior capsule of the knee (only muscle) and posterior side of the tibia. As it was mentioned in screw-home mechanism, popliteus is the only muscle that unlocks the knee joint after full extension of the knee. It also contributes the stability of the posterolateral corner of the knee joint.

Gastrocnemius

The gastrocnemius attaches to the medial femoral condyle with its medial head and attaches to the lateral femoral condyle with lateral head and inserts the posterior surface of the calcaneus via Achilles tendon. Although gastrocnemius is the strongest plantar flexor muscle, it also has a moment arm for knee flexion since it crosses the knee joint posteriorly. In terms of contributing knee flexion, Li et al. (2002) showed that gastrocnemius is

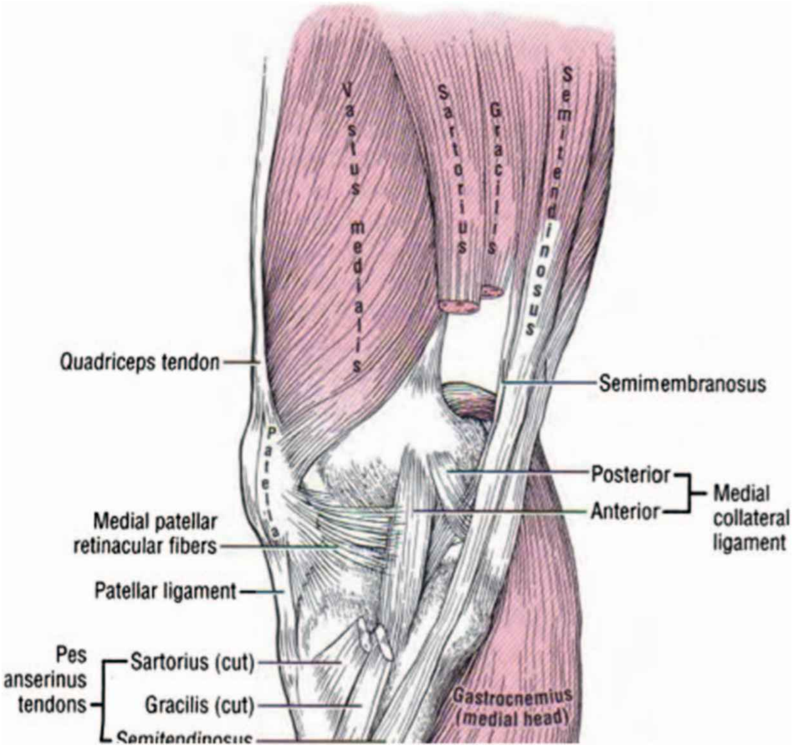

FIGURE 22.15 Posteromedial view of the knee joint.

more effective when the knee was to 10°−20° flexion from the full of knee extension.

Extension strength versus flexion strength

Extension strength at the knee is greater than flexion strength since the mass of extensor muscles is significantly larger than the mass of the flexor muscles (Li et al., 2002). Previous studies showed that maximum quadriceps strength to hamstring strength ratio may range from 45% to 65% (Murray et al., 1985; Calmels et al., 1997; Croce and Miller, 2006). However, the ratio could possibly be affected by the knee joint position, gender, injury, contraction type and speed (Aagaard et al., 1995; Hewett et al., 2008; Oatis, 2009). Hamstring to quadriceps strength ratio may increase when the contraction velocity increases (Aagaard et al., 1995). In higher angular velocities, hamstring quadriceps ratio is lower in females when compared to male counterparts (Hewett et al., 2008).

Tibiofemoral joint passive static restraints

Knee joint capsule

The knee joint capsule is the largest joint capsule of the human body. Articular capsule is form by fibrous capsule and synovial membrane. The fibrous capsule attaches posteriorly to the femoral and tibial condyles, continues medially and laterally and attaches the articular borders of the femur and the tibia. It merges with the tendinous expansions of the vastus medialis (medial retinaculum) and lateralis (lateral retinaculum) anteriorly and attaches to the patella and patellar tendon. The internal surface of the fibrous capsule is lined with a synovia membrane but two layers of the articular surface follow different routes (Oatis, 2009; Neumann, 2013).

The medial and lateral retinaculum plays an important role for controlling the patellar motion.

Meniscus

The menisci are two crescent-shaped cartilages that localized between the femoral condyles and the tibial plateau provide several crucial mechanical functions in the knee joint (Fig. 22.16) (Fox et al., 2012). They increase congruence between articular surface of the femur and the tibia. The menisci provide shock absorption to the knee joint during weight-bearing activities, assist the knee joint stability, contributing to proprioception of the knee joint and helps the lubrication of the articular surfaces (Voloshin and Wosk, 1983; Noyes and Barber-Westin, 2002).

The medial and lateral menisci are semilunar-shaped structures of fibrocartilage with three segments: an anterior horn/root, a body, and a posterior horn/root. The external edge of each meniscus is attached to the tibia and adjacent capsule by coronary ligaments. A transvers ligament connects the two menisci anteriorly (Rath and Richmond, 2000).

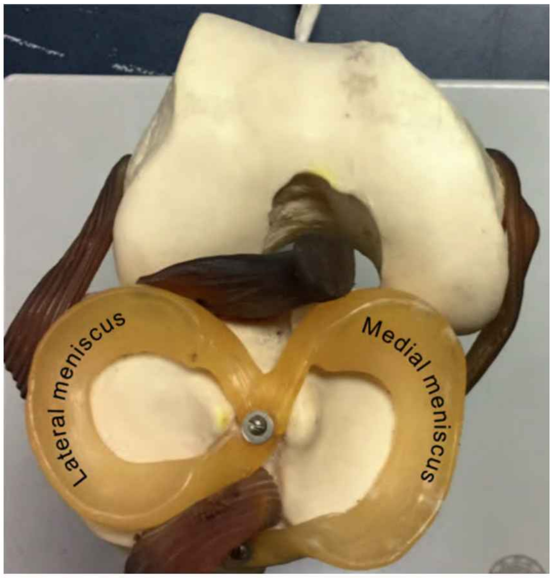

FIGURE 22.16 Medial and lateral menisci.

The anterior meniscofemoral ligament (ligament of Humphrey) and the posterior meniscofemoral ligament (ligament of Wrisberg) origins from lateral meniscus and attach to the medial femoral condyle.

Medial versus lateral meniscus

Lateral meniscus is more mobile than medial meniscus since the capsular attachment of the medial meniscus is more secure than the lateral meniscus (Rath and Richmond, 2000). During knee flexion, the femoral condyles glide posteriorly on the tibial plateau in conjunction with tibial internal rotation. The posterior translation of the lateral meniscus is greater than the medial meniscus during knee flexion (11.2 mm versus 5.1 mm) (Thompson et al., 1991). The medial meniscus a restraint to anterior tibial displacement with ACL (Levy et al., 1982) thus it is common to see meniscus injuries accompany to ACL injuries.

The menisci occupy 60% of the contact area between the tibial and femoral cartilage surfaces. It transmits 50% of compressive forces in a standing position (Krause et al., 1976; Fukubayashi and Kurosawa, 1980). When the knee is in 90° of flexion, the applied compressive forces are 85% greater than when it is in 0° of flexion (Ahmed et al., 1983). In full knee flexion, the lateral meniscus transmits 100% of the load in the lateral knee compartment, while the medial meniscus bears approximately 50% of the medial load (Walker and Erkman, 1975). A reduction in meniscal contact area due to meniscectomy reportedly produces more than 50% increase in peak joint-contact stresses (McDermott et al., 2018a,b; Verma et al., 2008), leading to the early development of osteoarthritis (Szomor et al., 2000; Pena et al., 2005; Noyes et al., 2012).

With the stretching of the circumferential bundles of the menisci, the menisci transmit loads from the femur to the tibia without extruding outside of the joint (Voloshin and Wosk, 1983) The meniscus and its horn attachments convert axial compressive forces to horizontal tensile stresses (hoop stress) (Jones et al., 1996). The distribution of hoop stresses helps to transmit axial loads across the knee joint surfaces, which prevents excessive cartilage loading (McDermott et al., 2018a,b).

Collateral ligaments

The primary function of the collateral ligaments is to limit excessive motion in the frontal plane. With the knee extended, the anterior part of the medial collateral ligament (MCL) provides the primary resistance against a valgus stress, while the lateral collateral ligament (LCL) provides the primary resistance against a varus stress. A secondary function of the collateral ligaments is to limit excessive knee extension. The collateral ligaments also helps to control extreme internal and external rotation when the knee is semi-flexed position (Fig. 22.13) (Griffith et al., 2009).

Medial collateral ligament versus lateral collateral ligament

The MCL is the largest soft tissue in the medial side of the knee that the length of the MCL is 8–10 cm (LaPrade et al., 2007). It attaches proximally to the medial femoral epicondyle and distally to the medial tibial condyle (Fu et al., 1994). It is composed of superficial and deep layers. The superficial component (tibial collateral ligament) is the primary restraint of the valgus stress. The deep component of the MCL is secondary restraint of the anterior tibial translation (Griffith et al., 2009). Griffith et al. (2009) suggest that primary function of the proximal and distal attachments of the superficial MCL are different. Proximal division of the MCL primarily resists valgus stress of the knee while the distal division primarily resist external and internal rotation. The LCL originates from the lateral femoral epicondyle and attaches to the lateral aspect of the fibular head. The length of the LCL is approximately 7 cm. It is the primary restraint of the varus stress especially between 5° and 25° of knee flexion (Grood et al., 1981). During knee flexion, lateral femoral condyle moves posteriorly toward the fibula that makes LCL as an external rotator contributor of the knee joint (Sugita and Amis, 2001).

Cruciate ligaments

The cruciate ligaments are intra-capsular structures but extra-synovial structures. The cruciate ligaments are

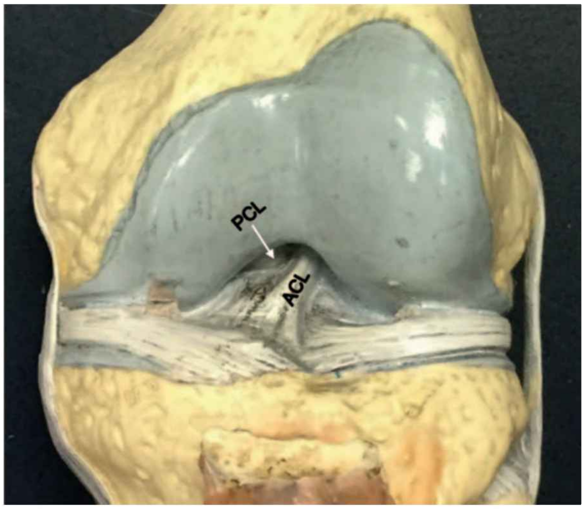

FIGURE 22.17 Anterior (ACL) and posterior (PCL) cruciate ligaments.

named base on their attachment to the tibia (Fig. 22.17). They provide most of the resistance to anterior-posterior shear forces between tibia and femur.

Anterior cruciate ligament versus posterior cruciate ligament

The anterior cruciate ligament (ACL) originates on the medial aspect of the lateral femoral condyle and inserts in the anterior intercondylar area of the tibia (Noyes and Barber-Westin, 2012). The ACL ranges from 31 to 38 mm in length and 10 to 12 mm in width (Amis and Dawkins, 1991). The ACL functionally consists of two bundles: anteromedial (AM) and posterolateral (PL). The two bundles are named according to their tibial insertion. Both bundles originate from the posteromedial side of the lateral femoral condyle and attach intercondylar tibial eminence anteriorly. Hollis et al. (1991) showed that AM bundle tightens flexion, while PL tightens in extension. The greatest forces transmitted through the AM bundle were at 60- 90° of flexion. The force was greatest for the PL bundle at full extension (Gabriel et al., 2004).

The ACL is the primary restraint to the tibial anterior translation relative to the femur. Sectioning ACL causes an increase in anterior tibial translation mostly between 15° and 45° knee flexion. Therefore, the most effective position for clinical examination of anterior knee instability is 30° of knee flexion (Lachman test) (Fukubayashi et al., 1982). The ACL also functions as a major secondary restraint to internal rotation, particularly when the joint is near full extension (Duthon et al., 2006). In addition, the ACL functions as a minor secondary restraint to external rotation and varus—valgus angulation, especially during weight-bearing conditions (Matsumoto et al., 2001; Duthon et al., 2006). The failure load and stiffness values of the ACL are 2160 ± 157 N and 242 ± 28 N/mm, respectively. These values decrease with age (Woo et al., 1991).

The posterior cruciate ligament (PCL) is the largest of the intraarticular ligaments and originates from the lateral aspect of the medial femoral condyle to the posterior intercondylar area of the tibia. The length of the PCL ranges from 32 to 38 mm long with an average width of 11—13 mm (Harner et al., 1999; Ahn et al., 2006). Like ACL, PCL consists of two distinct but inseparable bundles: anterolateral (AL) and posteromedial (PM) bundles (Makris et al., 2000). AL bundle is tauter in flexion while PM is tauter in extension. However, reciprocal relationship between the bundles of the ACL, PCL's AL and PM bundles have a codominant relationship (Ahmad et al., 2003). AL bundle becomes tighter during knee flexion but during deep knee flexion, AL bundle could not adequate to resist tibial posterior translation. PM bundle resist posterior tibial translation during deep flexion since its orientation becomes more horizontal with increasing knee flexion (Ahmad et al., 2003).

The PCL is the primary restraint to posterior translation of the tibia with respect to the femur and the secondary restraint to valgus-varus and external rotation. Isolated sectioning of the PCL resulted in 3-fold increase in posterior translation of the tibia compared to intact knee and the amount of posterior translation is the greatest at 75°of knee flexion (Fukubayashi et al., 1982).

Gait mechanics in acl-deficient knee

As the primary restraint in antero-posterior translation, the rupture of the ACL would cause instability in the knee. During walking, the ACL primarily control tibial anterior-posterior translation and internal-external rotation stability (Slater et al., 2017). The ACL deficient patients use stronger contraction of the hamstrings to pull tibia posteriorly or they walk with weaker contraction of the quadriceps to avoid pulling the tibia anteriorly (Chen et al., 2012). Thus, the patients are reported to show higher knee flexion from mid to late stance phase. When compared to healthy knees, displacement of the tibia in ACL-deficient knees is offset toward internal rotation and posterior translation in injured knee in stance phase (Andriacchi and Dyrby, 2005; Slater et al., 2017). Internal rotation and antero-posterior offsets are also shown to be correlated with the increased knee moments (Andriacchi and Dyrby, 2005). In swing phase, ACL-deficient knees, the tibial external rotation and anterior translation during knee extension is reduced (Andriacchi and Dyrby, 2005). The ACL has a critical role to prepare the knee during terminal swing to heel strike so the ACL deficiency leads so decreased tibial external rotation at heel strike (Andriacchi and Dyrby, 2005). This altered tibiofemoral joint motion is thought to affect cartilage loading and initiates cartilage degeneration (Slater et al., 2017).

Posterolateral corner restraints

The soft-tissue restraints of the posterolateral corner (PLC) of the knee joint consist of LCL, lateral head of gastrocnemius, popliteofibular ligament, popliteus tendon, biceps femoris tendon, ITB and the arcuate ligament (Barker et al., 2009). PLC structures primarily resist excessive varus and external rotation stresses.

Isolated PLC injury, which is rarely occurs, causes a pattern of increased varus laxity, tibial external rotation, and a change in tibial coupled rotation. Isolated sectioning of the PLC leads a significant increase in tibial external rotation from 18° to 31° at 30° of knee flexion with gross tibial compartment translation of 8 mm (Sugita and Amis, 2001; Sekiya et al., 2005). Injury to the LCL, popliteus tendon, and popliteofibular ligament increase in varus more than 5 mm near extension (15°) (Grood et al., 1988).

Patellofemoral joint restraints

Medial patellofemoral ligament

The medial patellofemoral ligament (MPFL) is a thin fascial band approximately 53 mm long that links from the region of the medial epicondyle of the femur to the proximal part of the medial border of the patella (Tuxoe et al., 2002). The patellar attachment of the MPFL is usually wider than the femoral attachment (Amis et al., 2003).

MPFL is the primary passive restraint that contributes 50–60% restraint of lateral translation of the patella (Desio et al., 1998; Hautamaa et al., 1998; Amis et al., 2003; Melegari et al., 2008). In particular, it controls the lateral translation of the patella during the first 30° of knee flexion before the patella contacts with the trochlear groove (Bicos et al., 2007; Bollier et al., 2011).

Medial and lateral retinaculum

Some fibers of vastus medialis extends more distally from the attachment side of the patella to make up medial retinaculum. Medial retinaculum provides 11% of the restraining force to the lateral patellar translation (Conlan et al., 1993). Lateral retinaculum, on the other hand, is made up by the anterior fibers of the iliotibial band and vastus lateralis expansions. Lateral retinaculum controls the lateral movement of the patella, and it provides resistance against lateral displacement of the patella (Desio et al., 1998) (Fig. 22.13).

İliotibial band

The iliotibial tract (ITT) is the most superficial layer of the lateral aspect of the knee composed of fascial expansions of tensor fascia lata, gluteus maximus and gluteus medius (Fig. 22.18). It is a broad layer that attaches onto Gerdy's tubercle in the anterolateral aspect of the tibia. It also attaches patella via lateral retinaculum. ITT has an important role for lateral stabilization of the knee (Cooper et al., 2006). It restraints varus stress and acts as an extensor in full extension and as a flexor after 40° of knee flexion. The tightest angle of the ITT is between 10° and 30° of knee flexion where it is more vulnerable to injuries (Chen et al., 2000).

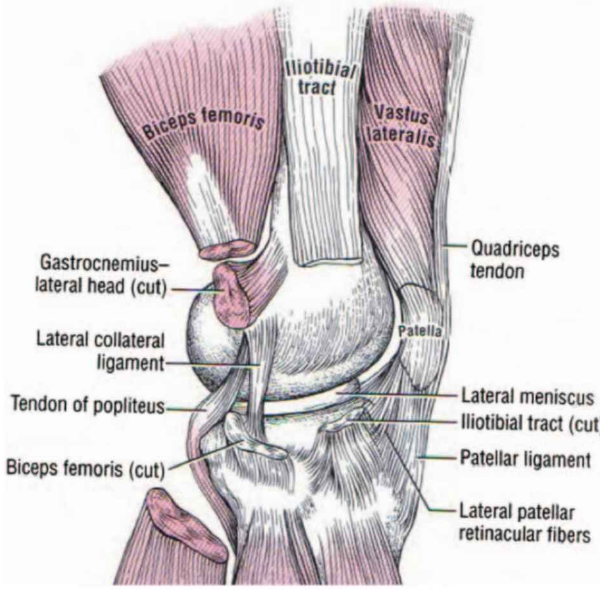

FIGURE 22.18 Lateral view of the knee joint. The iliotibial tract is the most superficial layer of the lateral aspect of the knee composed of fascial expansions of tensor fascia lata, gluteus maximus and gluteus medius.

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Chapter 23

Ankle and foot complex

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Introduction

The foot and ankle is a complex joint capable of handling tremendous stress and possessing the ability to compensate to a wide variety of unpredictable forces. The foot, as the only part of the body that contacts the ground during single leg standing, needs to be sufficiently stable to maintain the centre of mass within the base of support. As force generators, foot muscles (including extrinsic and intrinsic foot muscles) contribute to stability of the foot itself and the whole body. Movement of the foot and ankle is multiplanar and all the components move simultaneously in coordination.

Ankle and foot complex consist of distal tibia and distal fibula, seven tarsals, five metatarsals and 14 phalangeal bones. With many contractile and non-contractile structures work in a perfect synchronization to meet the requirement of very distinctive functions of the human foot during bipedal weight bearing, walking, running and jumping and other different activities performed in daily life.

Bones of the ankle and foot

Tibia

The distal tibial shaft is medially enlarged and ended with medial malleolus (Drake et al., 2015). The lateral surface of the medial malleolus is in contact with the medial surface of the talus and these two articular surfaces form lateral part of the ankle joint. The lateral surface of the medial malleolus continues horizontally as the distal surface of tibia and contacts with the superior surface of the talus. Distal surface of the tibia is concave in antero-posteriorly and convex in medio-laterally. Distal lateral part of the tibia forms tibio-fibular joint with distal fibula. Posterior part of the distal tibia continues inferiorly from tibiofibular joint to the medial malleolus. Posterior margin of the distal tibia exceeds the posterior margin of the talus inferiorly and this posteriorly enlarged part is called posterior malleolus (Fig. 23.1), prevents excessive plantar flexion of the ankle joint (Boraiah et al., 2008; Abdelgawad et al., 2011; Miller et al., 2012).

The distal tibia of the adult is in external rotation with respect to its proximal part that is called normal external tibial torsion (Fig. 23.2) (Kling and Hensinger, 1983; Staheli, 1987; Schneider et al., 1997). However, excessive external tibial torsion affects the foot functions in static and dynamic conditions. Tibial torsion can be measured using variety of methods from a simple one available in a clinical setting to computerized tomographic image in a laboratory condition (Jacob et al., 1980; Sayli et al., 1994; Schneider et al., 1997; Milner and Soames, 1998). One of the simple methods to measure tibial torsion is to have the patient sit with the legs hanging over the edge of the examination table and the angle formed by the second metatarsal ray and the tibial tuberosity gives the tibial rotation. While newborns show slight external tibial torsion, even medial torsion turns 20°–40° external torsion in their adult age (Staheli, 1987; Yoshioka et al., 1989; Sayli et al., 1994; Schneider et al., 1997; Milner and Soames, 1998; Seber et al., 2000).

Fibula

Fibula is located at the lateral side of the tibia and ends inferiorly with the lateral malleolus. Medial surface of the lateral malleolus contacts with the lateral surface of the talus forming the lateral part of the ankle joint and provide muscle attachment for the extrinsic muscles of the ankle and foot. The proximal end of the fibula articulates with the inferior aspect of the lateral tibial condyle, forming the proximal tibiofibular joint. While lateral collateral ligament and biceps femoris tendon are attached to, the

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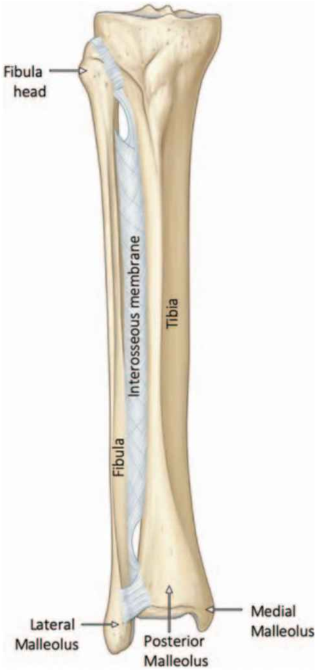

FIGURE 23.1 Tibia and fibula. (a) Anterior view, (b) Posterior view of tibia. *Reprinted with permission from Elsevier, Drake et al., 2015.*

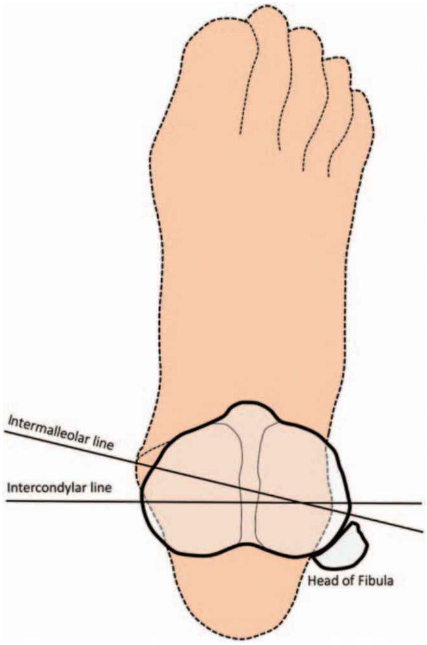

FIGURE 23.2 Tibial torsion. *Reprinted with permission from Istanbul Tıp Kitabevleri, Angın, 2016.*

fibular head directly associates to the knee dynamics. Although, these ligament and muscles are not directly related to the ankle and foot, any abnormal condition could affect the ankle function.

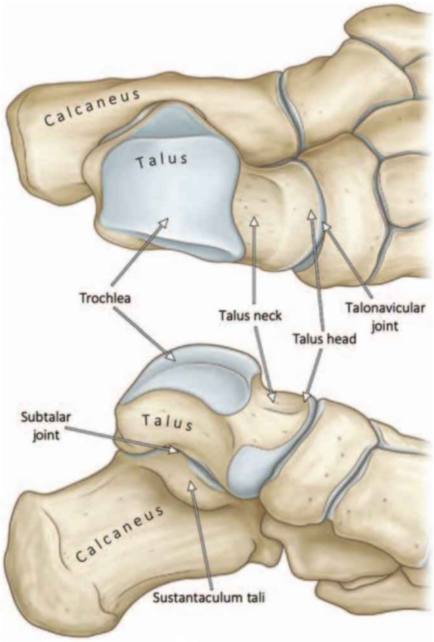

FIGURE 23.3 Talar dome, talus head and neck, joints between talus and its neighboring structures. *Adapted with permission form Elsevier, Drake et al., 2015.*

Tarsal bones

The tarsal bones provide connection between the lower extremity and the foot, which they have mobile structure for accommodate different movements as they have stabile structure for weight bearing. The proportional length of all tarsal bones (tarsus) is greater within the whole foot compared with that of other primates as the ratio of the relative tarsal length to the total foot length was found 53.3% in humans versus 27.2–34.9% in most other primates (Schultz, 1963; Le Minor and Wolff, 2004; Pietak et al., 2013). This evidence shows specific characteristics of the human foot compared with all other primate feet due to its adaptation to erect posture and bipedalism (Cunningham et al., 2010; McNutt et al., 2018).

Talus

Talus provides connection between ankle and lower extremity and does not have a muscle attach to it (Bartonicek et al., 2018). The forces transmitted to the talus by neighboring structures control its movements. Talus has three anatomic landmarks: The talar body at the proximal, talar head at the distal and talar neck at the middle, which connects these two portions (Fig. 23.3). Talar body articulates with the tibia at proximal and medial sides and with fibula at the lateral side while it articulates with calcaneus inferiorly. Superior surface of the talar body that called talar dome or trochlea is anteroposteriorly convex and mediolaterally concave, therefore it shows high congruency with distal surface of the tibia termed mortis (Fig. 23.4) that is necessary for load bearing in both static and the dynamic conditions (Vetter et al., 2019). This superior articular surface of the talus is also wider in its anterior portion. The medial articular surface of the talar body is smaller than its triangular shape lateral articular surface (Mueller, 2005). Because of this discrepancy, movement axis of the ankle joint is not parallel or perpendicular to any movement plane (Fig. 23.5).

The neck of the talus resites between head and body, which is the narrow region with rough suface for the attachment of ligaments. It forms a roof to the sinus tarsi after articulation of talus and calcaneus. The long axis of the neck creates 150° angle with the body and inclined downwards, distally and medially. This angle is 130°−140° at birth (Standring, 2016).

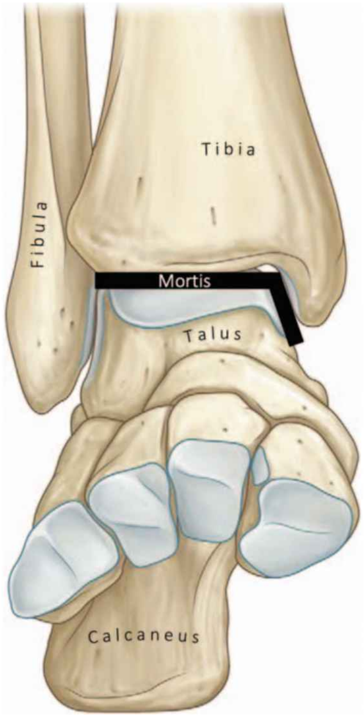

FIGURE 23.4 Mortis. *Reprinted with permission from Elsevier, Drake et al., 2015.*

Head of the talus directed infero-medially, has a distal surface, which is ovoid and convex; its long axis is also inclined infero-medially to articulate with the proximal navicular surface. This direction of the talar head leads the distal segments of the medial longitudinal arch, and foot may be appeared to be in more pronation as this inclination increases.

Three inferior facets of the talar head, the anterior, middle and posterior articulate with the calcaneus. A triangular inferomedial facet that is localized medially to the anterior calcaneal facet at the talar head articulates with the plantar calcaneonavicular (spring) ligament. The highly inconsistent facet is situated on the anterolateral part of the head of the talus, which contact with the lateral calcaneonavicular ligament (Bartonicek et al., 2018). The posterior inferior articular surface of the talar head rests on the sustentaculum tali, the shelf-like prominence of the medial calcaneus. These three facets may be blended into a single facet and even fusions of all articular facets, including the posterior facet at the talocalcaneal joint (Prasad and Rajasekhar, 2018).

The trochlea of the human talus receives compressive forces from the tibia and fibula (Michelson et al., 2001), and talar body transmits the force to the calcaneus through vertical trabeculae while the talar head directs the forces anteriorly to the navicular via horizontal trabeculae during standing, walking, and running (Sinha, 1985; Pal and Routal, 1998).

Calcaneus

Calcaneus is the largest tarsal bone that sites at most posterior region of the foot and provides short lever arm for Achilles tendon (Le Minor and Wolff, 2004; Keener and Sizensky, 2005; Standring, 2016). The superior surface articulates with the talus; the distal surface articulates with the cuboid; the medial surface called the sustentaculum tali supports the head of the talus. The posterior

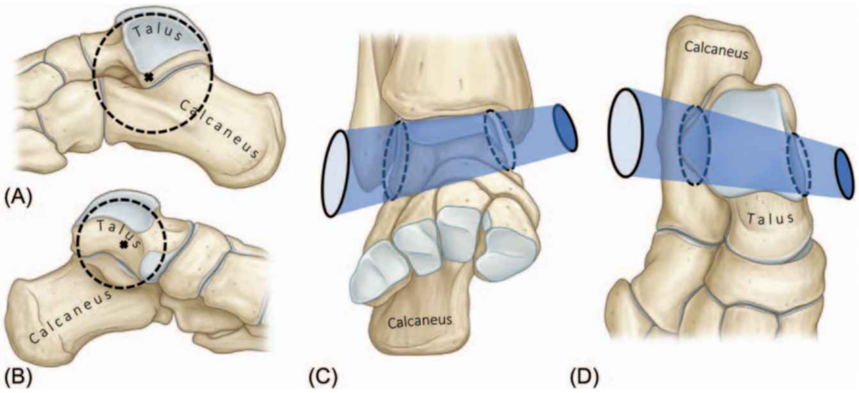

FIGURE 23.5 Geometrical shape of talar surfaces and ankle joint axis: (A) lateral joint surface, and (B) medial joint surface of the talus, (C) front view and, (D) superior view of the ankle joint axis positions. Variations in the position of the joint axis is represented as cone with ends cut off, and larger end facing laterally. *Adapted with permission from Elsevier, Drake et al. 2015.*

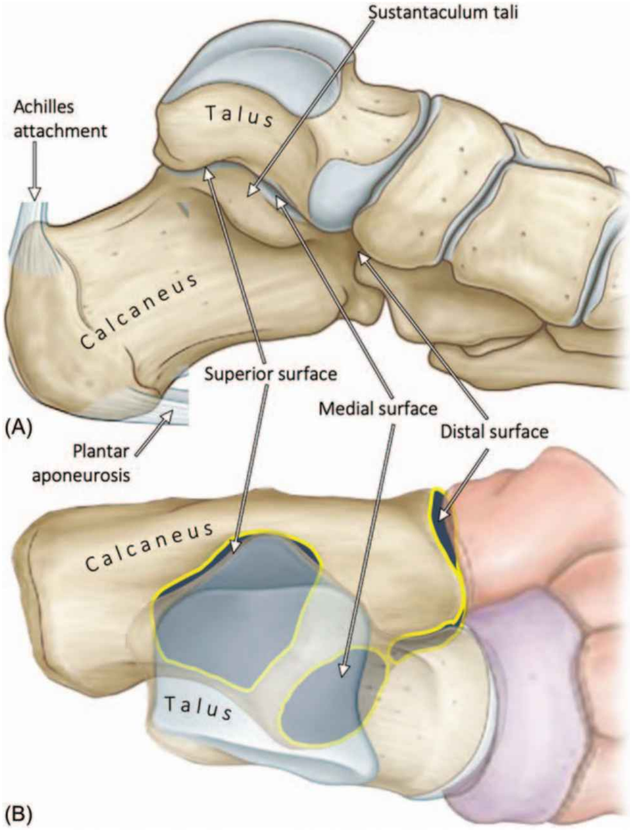

FIGURE 23.6 Calcaneus, (A) medial view, (B) superior view shows joint surfaces. *(Adapted with permission from Elsevier, Drake et al. 2015.*

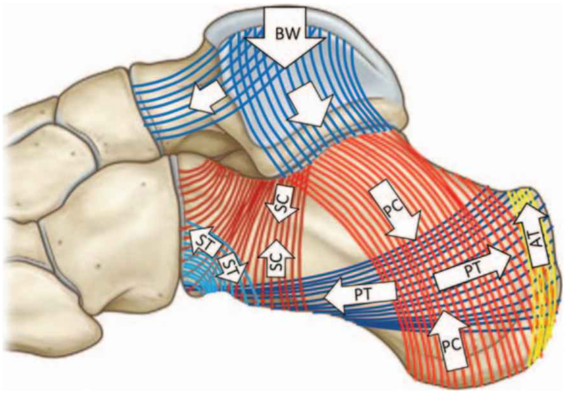

FIGURE 23.7 Load transfer pattern of calcaneus: Body weight (BW), primary compression lines (PC), secondary compression lines (SC), primary tensile lines (PT), secondary tensile lines (ST), Achilles tendon lines (AT). *Adapted with permission from Elsevier, Drake et al., 2015.*

surface provide attachment place for the Achilles tendon; the roughed inferior surface forms the major weight bearing area of the calcaneus (Keener and Sizensky, 2005). This surface provides attachment for the plantar aponeurosis, plantar muscles and ligaments (Fig. 23.6).

The calcaneus is well designed to sustain high tensile, bending, and compressive forces (Fig. 23.7) (Hall and Shereff, 1993; Wong et al., 2016). It possesses a thin shell of cortical bone that encloses a sparse but highly organized array of trabecular bone (Fielding and Kraft, 2014). The relatively sparse cancellous bone within the calcaneus leaves space that is filled by blood. This high fluid content helps the calcaneus to function as a hydrodynamic shock absorber during impact (Grimm and Williams, 1997).

Human erect posture and movement require specific trabecular pattern of calcaneus (Nichols et al.; Bajraliu et al., 2016). The major load bearing column are in a path between the posterior articular surface of the talus and the heel. Secondary compression occurs in a trabecular group between the talus and the posterior calcaneal surface. The primary tensile load system is located between the Achilles tendon the arch of the foot (Gefen and Seliktar, 2004). The area with insignificant trabecular structure is known as the "neutral triangle" (Daftary et al., 2005; Fielding and Kraft, 2014). Certain species that falls from height, or have leaping function have a foot anatomy that effectively sustains the force of such falls because of their longer calcaneus without neutral triangle and high load sharing capacity of muscles (Bajraliu et al., 2016). Presence of this neutral triangle however, may simply be a manifestation of a fracture in the human calcaneus from axial loading, such as falling from height (Galluzzo et al., 2018).

Navicular

The navicular is a boat like shaped bone located in medial side of the foot and plays a significant role as a keystone of the medial longitudinal arch(Rosenbaum et al., 2014; Rosenbaum et al., 2015). It connects the talar head proximally to the three cuneiform bones distally. Medial surface projected medially as a prominent tuberosity called medial navicular tubercle, which is clinically significant landmark for biomechanical modeling of the foot. Navicular tubercle can be palpated approximately 2.5 cm distal and plantar to the medial malleolus (Standring, 2016). Lateral surface of the navicular articulates with cuboid bone (Fig. 23.8). The navicular transfers the load from the talar head to the forefoot, specifically medial three metatarsals (Chan and Rudins, 1994). During the midstance phase of the walking, the dorsal side of navicular receives von Mises stress about 3.3 MPa, and the medial plantar side of navicular receives 2.6 MPa. This stress increases at the dorsal side of the navicular to 7.6 MPa during push-off phase (Jacob and Patil, 1999).

Cuneiforms

The cuneiform bones form a unique series of bone tightly bound together and function as a unit. They articulate

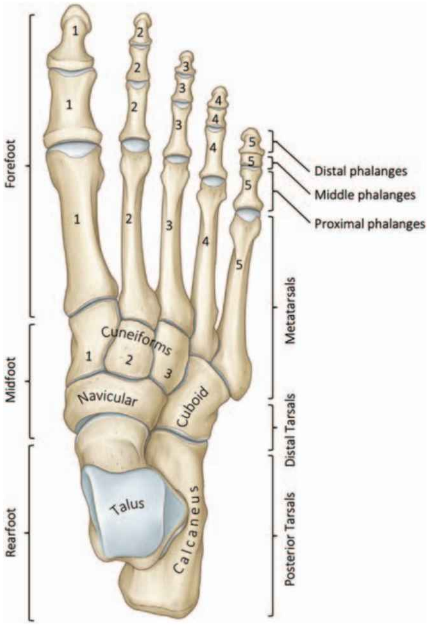

FIGURE 23.8 Functional units of the foot. *(Reprinted with permission from Elsevier), (Drake et al. 2015).*

with the navicular proximally through three separate facets and with metatarsal segments distally. Laterally, the third cuneiform articulates with the wedge like medial third of the cuboid. This orientation supports the third cuneiform (Vogler and Bojsen-Moller, 2000). The dorsal surfaces of the intermediate and lateral cuneiforms form the wedge that shape the transverse arch. Higher dorsal compression forces increase the transverse width of the combined dorsal dimensions of these three units compared to their plantar dimensions, and therefore form the wedge (Fig. 23.8) (Vogler, 1987).

Cuboid

The cuboid is a wedge-shaped bone, and is the only bone that supports the lateral column (Pountos et al., 2018) It lies between the calcaneus, and the fourth and fifth metatarsals (Oatis, 1988). The medial surface articulates with the lateral cuneiform (Fig. 23.8) (Pountos et al., 2018). In a dynamic condition however, cuboid bone works with navicular as a functional unit (Wolf et al., 2007). The dorsal calcaneal and medial cuboid tuberosities, together support the calcaneocuboid joint during weight bearing with help of strong ligaments. The importance of the cuboid bone that it is involved in all intrinsic movements of the foot (Sangeorzan and Swiontkowski, 1990). While there is limited movement in the calcaneocuboid joint, all the movement of the lateral column occurs at the tarsometatarsal joints. Similar to carpo-metacarpal joints in the hand, the range of motion at the lateral tarsometatarsal joints is up to three times higher than that of the medial tarsometatarsal joints when individually compared (Greiner and Ball, 2014). The cuboid acts as a fulcrum during the contraction of the peroneus longus. The peroneal sulcus is located at the plantar surface of the cuboid and runs distally and medially, provides a pulley for peroneus longus tendon (Donatelli, 1985).

This bone had a very thin covering of compact bone. Pressure trabeculae extended from the proximal surface which articulated with the distal surface of the calcaneus. These trabeculae denser towards the distal surface and less dense towards the facet for the lateral cuneiform. These weight bearing trabecular lines were intersected proximally and distally at right angles by tension trabeculae, but larger and irregular in shape in the central region compared with those placed more proximally and distally (Sinha, 1985). As the bones of the midfoot are all relatively shorter in chimpanzees, this elongation of the midfoot in humans indicates to convert the foot into a more effective lever during the late stance of the gait (Pountos et al., 2018).

Metatarsals

The general structure of the metatarsals consists of a pyramidal base, convex in shape and long shaft, and a spherical head that together function to distribute weight bearing forces and form the metatarsal arch. Each metatarsal extends anteriorly at an ideal length, parallel to one another. The first metatarsal is considered the shortest one, while the second metatarsal is the longest and counted as the midline of the foot (Stoupine and Singh, 2018). However, individuals may have their first metatarsal bone longer than the lateral fours. Two sesamoid bones located under the hallux, at the distal end of the first metatarsal bone. Basis of the second metatarsal bone is extended proximally and accommodated firmly into the recess formed by the three cuneiform bones. Because of this position, risk of stress fracture may be higher in the second metatarsal bone particularly in athletes (Standring, 2016). The basis of the fifth metatarsal bone also extended proximally.

Length of the metatarsal bones affects the forefoot loading characteristics (Al-Munajjed et al., 2016). As there is no consensus about normative value in the metatarsal length, Barrôco et al. (2015) developed a formula for metatarsal length standardization and they have found short first metatarsal (index minus) compared to second metatarsal was approximately 71–74% in the study group for both males and females. This morphotype of the foot is described as Greek foot, while the foot with longer first metatarsal is described as Egyptian foot. The foot morphotype with equal length of first and second metatarsal bones called Roman foot (Ali et al., 2018).

Phalanges

There are two phalanges at the big toe (hallux), while each of the lateral four toes have three phalanges. Each phalanx has concave surface at the proximal end and convex surface at the distal ends (Standring, 2016). The phalanges in the foot are shorter than those in the hand, and their total length is also shorter than the metatarsals. Proportional length of tarsal, metatarsal and phalanges is 3:2:1 in the foot, while proportion of carpal, metacarpal and phalanges in the hand is 1:2:3. This indicates that foot is a stable structure compared to mobile hand.

Joints of the ankle and foot

The foot is consisted of three functional parts as rearfoot, midfoot and forefoot (Fig. 23.8) (Fraser et al., 2016). The anatomical borders of these regions are formed by the foot bones. The rearfoot is made up of the talus and calcaneus. This region is the first part of the foot that meets with ground reaction forces as it hits the ground. Therefore, this part influences the functions and movements of other two parts.

The mid foot is made up of the navicular, the cuboid and the three cuneiform bones. This part supports the mobility and the stability of the foot and transfers motion and the forces acting on from hindfoot to the forefoot.

The forefoot is formed by five metatarsal bones and all the phalanges together. Forefoot has ability to adapt to the level of the ground and acts as a support point during terminal stance phase of the walking (Oatis, 2009; Standring, 2016).

The cornerstone structure of the ankle and foot joint complex is the talus. Because of its articulations with adjacent bones, nearly 70% of whole surface covered by articular surfaces. Moreover, it is mechanically involved in three major joints of this complex: talocrural, subtalar and transvers tarsal.

From a clinical perspective; plantarflexion, dorsiflexion, supination and pronation is mostly used to describe motion in the ankle and foot complex (Lippert and Minor, 2011). It is worthy to note that all axes of the foot are oblique to the cardinal planes of the body. Therefore, there are combined movements, it is not a single determined motion around a single axis. For instance, abduction and eversion accompany with ankle dorsiflexion movement while inversion and adduction accompany with plantar flexion of ankle (Wright et al., 1964).

Proximal tibiofibular joint

Proximal tibiofibular joint has a synovial structure that makes gliding motion. It is supported by anterior and posterior tibiofibular ligaments together with joint capsule. The interosseous membrane lies between tibia and fibula and controls both proximal and distal tibiofibular joint. Proximal part of the tibiofibular joint motions is limited, most of the rotation occurs at the distal part of the tibiofibular joint (Radakovich and Malone, 1982). This joint functions to dissipate the torsional stresses applied at the ankle joint if any abnormal condition such as tightness of iliotibial band attaches to the fibular head (Lippert and Minor, 2011).

Distal tibiofibular joint

Distal tibiofibular joint is a syndesmosis type joint between the concave distal tibia and the convex distal fibula. There is no joint capsule due to its non-synovial joint structure. This joint is supported by interosseous membrane and several ligaments such as distal and posterior tibiofibular ligaments and medial collateral ligaments. Movement is limited at the tibiofibular joints and distal tibiofibular joint appears to be primarily related with ankle dorsiflexion (Oatis, 2009; Standring, 2016).

The ankle joints

The ankle joint is formed by the distal tibia on the talus with the fitting of the medial malleolus around the medial aspect of the talus, and the lateral malleolus of the fibula fitting around the lateral aspect. This type of joint often is referred as mortise joint. The concave shape of the proximal part of the mortise is reiforced by ligaments. The joint surfaces of ankle congruent each other properly and provides a stability of the ankle joint. However, when the joint is in the neutral position superior part of the talus is loaded. In an experimental study showed that contact surface area increases %10 under the 490 N load, but contact area increases to 15% when load was increased to 980 N (Calhoun et al., 1994) During standing 90–95% of the compressive forces transferred by talus and tibia and rest of the transferred by the lateral region of the talus and the fibula. In response to peak forces the ankle joint can be compressed by 30–40%. This shock absorption mechanism protects the intra-articular subchondral bone from degenerative stress (Neumann, 2010; Lippert and Minor, 2011). Although it is thinner, but it firmer than the cartilage of hip and knee joints.

The synovial capsule and the surrounding collateral ligaments are non-contractile supporters of the talocrural joint. Articular capsule is made up of several layers toward anterior and posterior. These layers allow plantar and dorsiflexion movement by folding and unfolding. The ligaments adding a mechanical support to the ankle joint and articular capsule, serve as proprioceptive source as they have mechanoreceptors; free nerve endings and Ruffini endings.

These collateral ligaments are called as medial and lateral collateral ligaments where the medial collateral ligament is larger and stronger than the lateral one. They control movements occurred at the tibiotalar and subtalar joints beside its stabilizing function (Leardini et al., 1999a,b). Since proximal joint surface of the talus is wider than that of posterior (Fig. 23.9) (Drake et al., 2015), this conical shape also prevents excessive dorsiflexion. On the other hand, any limitation in the distal tibiotalar joint limits the ankle dorsiflexion (Fujii et al., 2010; Hermans et al., 2010).

Medial collateral ligament or **deltoid ligament** (Fig. 23.10) is attached the distal medial malleolus. It consisted of tibionavicular ligament (anterior fibers), tibiospring ligament, tibiocalcaneal ligament (middle fibers) and tibiotalar ligament (posterior fibers) (Fig. 23.11). In brief, a triangular-shaped deltoid ligament, where apex is located along the tip of the medial malleolus, spreading out to attach to the talus, navicular, and calcaneus in four parts (Lippert and Minor, 2011; Drake et al., 2015). Anterior and posterior tibiotalar fibers are strong ligaments of the tibiotalar joint. They attach along the medial surface of the talus, close to the talocrural joint line. The deltoid ligament with superficial and deep fibers reinforces the medial side of the talocrural joint. The orientation and localization of these fibers limit the extreme motion of eversion across the talocrural, subtalar and talonavicular joints. It also resists valgus stresses coming from lateral to medial side of the ankle and subtalar joints (Savage-Elliott et al., 2013; Angın, 2016). It prevents lateral tilt of the talus. It is not common to damage deltoid ligament by excessive eversion due to its strong structure. The bony block occurred by the lateral malleolus is an additional factor to protect the ligament from excessive eversion injury (Savage-Elliott et al., 2013).

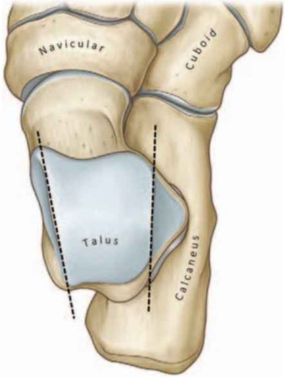

FIGURE 23.9 Joint surface of the talus is Larger at the anterior region. *(Adapted with permission from Elsevier), (Drake et al. 2015).*

Lateral collateral ligament is consists of anterior and posterior talofibular, and calcaneofibular ligaments (Fig. 23.12). Anterior and posterior talofibular ligaments directly support the ankle joint while calcaneofibular ligament supports both ankle and subtalar joint. The weaker anterior talofibular ligament attaches the lateral malleolus to the talus. Posteriorly, the strong posterior talofibular

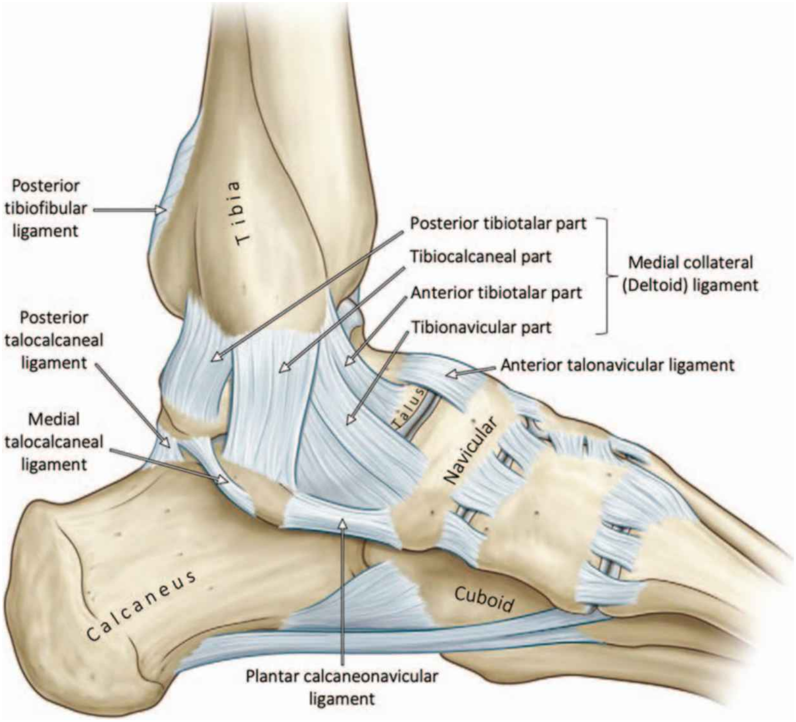
Posterior tibiofibular ligament
Tibia
Posterior tibiotalar part
Tibiocalcaneal part
Anterior tibiotalar part
Tibionavicular part
Medial collateral (Deltoid) ligament
Posterior talocalcaneal ligament
Anterior talonavicular ligament
Talus
Medial talocalcaneal ligament
Navicular
Calcaneus
Cuboid
Plantar calcaneonavicular ligament

FIGURE 23.10 Medial collateral ligaments; one of the strongest ligaments in the human body. *Reprinted with permission from Elsevier, Drake et al. 2015.*

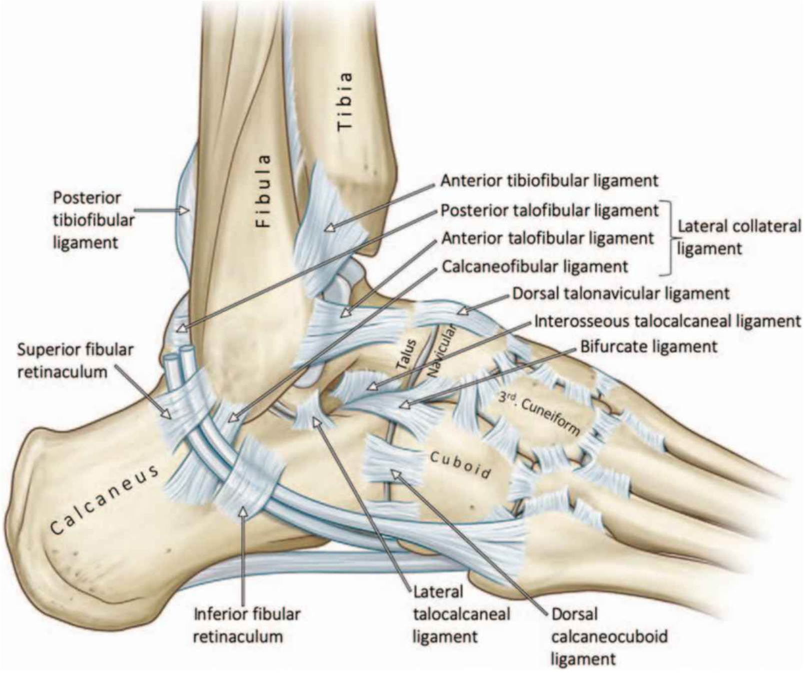
Tibia
Fibula
Posterior tibiofibular ligament
Anterior tibiofibular ligament
Posterior talofibular ligament
Anterior talofibular ligament
Calcaneofibular ligament
Lateral collateral ligament
Dorsal talonavicular ligament
Interosseous talocalcaneal ligament
Bifurcate ligament
Superior fibular retinaculum
Talus
Navicular
3rd. Cuneiform
Cuboid
Calcaneus
Inferior fibular retinaculum
Lateral talocalcaneal ligament
Dorsal calcaneocuboid ligament

FIGURE 23.11 Lateral ligaments of the ankle and midtarsal joints. *Reprinted with permission from Elsevier, Drake et al. 2015.*

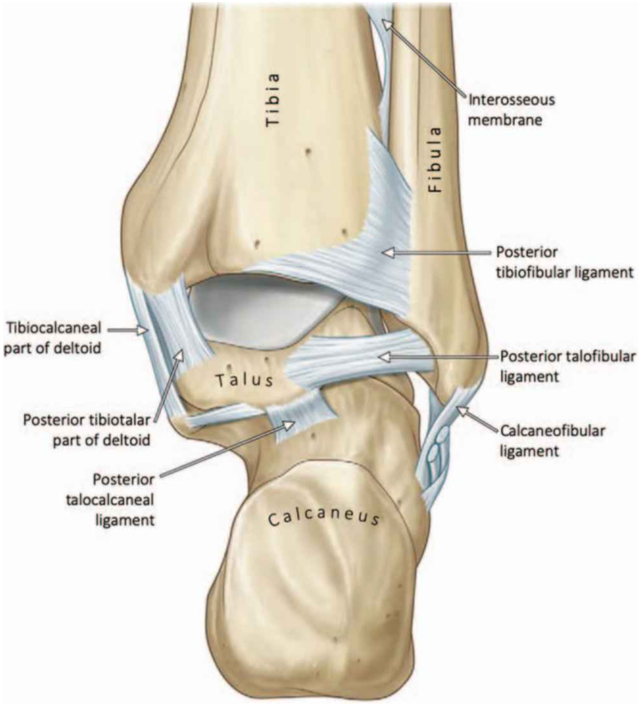
Tibia
Fibula
Interosseous membrane
Posterior tibiofibular ligament
Tibiocalcaneal part of deltoid
Talus
Posterior talofibular ligament
Posterior tibiotalar part of deltoid
Calcaneofibular ligament
Posterior talocalcaneal ligament
Calcaneus

FIGURE 23.12 Ligaments of ankle joint; posterior view. *Reprinted with permission from Elsevier, Drake et al. 2015.*

ligament runs horizontally to connect the lateral malleolus to the talus. Long and vertical calcaneofibular ligament at the middle attaches the malleolus to the calcaneus. The lateral collateral ligaments limit the excessive inversion motion of the ankle. Most of these fibers located obliquely varying anterior and posterior direction therefore, control extreme of dorsiflexion and plantar flexion of ankle joint (Neumann, 2010; Lippert and Minor, 2011).

Movement at the ankle joint

The movement of the foot compared to the lower extremity is the sum of movements occurring between the tibia, fibula, tarsal and metatarsal bones. Information about the contribution of each joint to this total movement gives important clues about the movement ability of the foot.

The ankle joint is a hinge-type joint that its axis of motion partially passes through the malleolus. The cylinder-shaped superior surface of the talus with 2 cm radius articulates with tibia. The talar facet covers 140° of this cylinder while facet of the tibia has 70° of contact area within the joint (Fig. 23.13) (Kapandji, 2011). The angular difference between these joint surfaces determines range of movement of the tibiotalar joint (Lundberg et al., 1989a). Therefore, ankle dorsiflexion and plantar flexion movement ranges are 20°, and 50° respectively.

In the closed kinematic system, tibia rotates forward around the centre of the talar arch and moves the ankle joint into dorsiflexion. When it is rotating backward, tibiotalar joint moves into plantar flexion. During these movements, the contact area between talus and tibia changes (Calhoun et al., 1994). Contact area is shifts anteriorly as the ankle joint moves into dorsiflexion while plantar flexion leads posterior shift of the contact area.

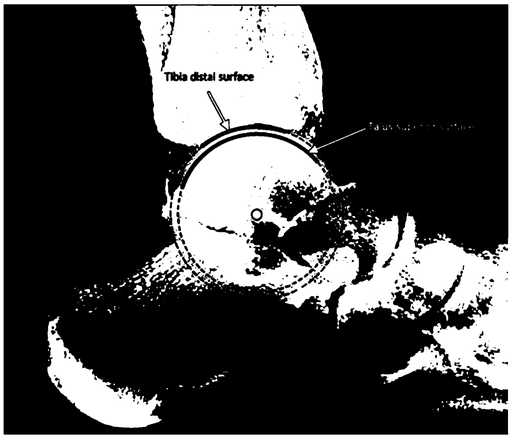

FIGURE 23.13 Proximal joint surface of the talus has a cylindrical shape with 2 cm radius and 140° arch angle that congruent to distal tibial surface with 70° arch angle. Uncovered talar joint surface allows to tibia rotates and creates ankle range of motion. *Adapted with permission from Elsevier, Drake et al. 2015.*

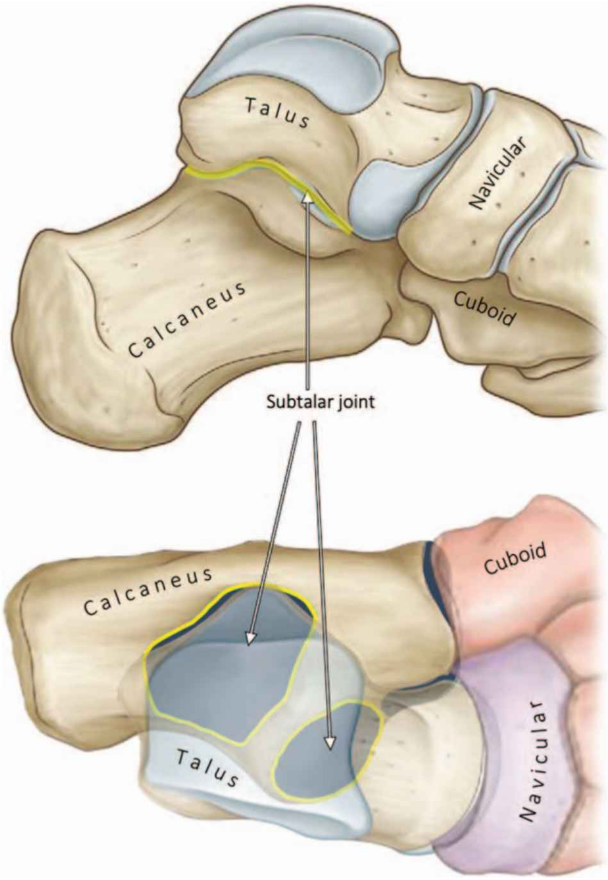

FIGURE 23.14 Subtalar joint. *Adapted with permission from Elsevier, Drake et al. 2015.*

İnversion shifts the contact area medially and eversion shifts laterally with eversion.

Dorsi-plantar flexion of ankle is accompanied by rotation of talus, rotation and gliding of the fibula. During dorsiflexion, external rotation is occurred at talus and fibula with respect to the tibia. Although it is considered as simple hinge type joint, all these movements show complexity of ankle joint motions. On the other hand talus moves mediolateral direction between distal part of tibia and fibula to get involved in 1/3 of pronation and supination movement (Lundberg et al., 1989b, Hintermann and Nigg, 1995).

The ankle joint has 3° of freedom and rotation, mediolateral, antero-posterior in three planes and translational movements in the longitudinal axis. Dorsiflexion is associated with slight abduction and eversion and plantar flexion with slight adduction and inversion because of deviation of the axis from horizontal and frontal plane (Siegler et al., 2005; Wong et al., 2005; Lippert and Minor, 2011). At the initial stage of push of phase of walking gait, ankle joint is fully dorsiflexed, which is most stable and congruent position.

Subtalar joint

Subtalar joint is made up of articulation between three joint surfaces inferiorly talus with three joint surfaces superiorly calcaneus (Fig. 23.14) (Drake et al., 2015; Bartonicek et al., 2018). Subtalar joint functions as a bridge between foot and ankle; transferring loads from foot to tibia or from tibia to foot. It helps the foot to action like a pivot against sudden change of direction. To fulfill these features subtalar joint should allow the movement as needed and at the same time it must be stable to be able to bear the load. Saddle shaped posterior surface is larger than the others and has three movement planes. Anterior joint surfaces have primarily gliding motion because of their flat structure. Beside bony structures and their configurations, there are several strong ligaments provide joint stabilization (Perry, 1983; Angın, 2016).

The larger posterior surface of the subtalar joint is reinforced by **calcaneofibular**, **deltoid** (tibiocalcaneal fibers), **interosseous** (talocalcaneal) and **cervical ligaments**. The calcaneofibular ligament that limits the excessive inversion and the deltoid ligament that limits the excessive eversion were described previously within the ankle joint. The interosseous and cervical ligaments bind the talus with the calcaneus and limit all extreme motion of the subtalar joint but dominantly the inversion motion. Collateral ligaments of the ankle joint also support subtalar joint. Subtalar eversion is controlled by deltoid ligament, while lateral collateral ligament controls the inversion motion (Renstrom et al., 1988; Stephens and Sammarco, 1992; Luo et al., 1997).

Movement at the subtalar joint

Movement at the subtalar joint is triplanar around the single oblique oriented axis. The subtalar axis inclined

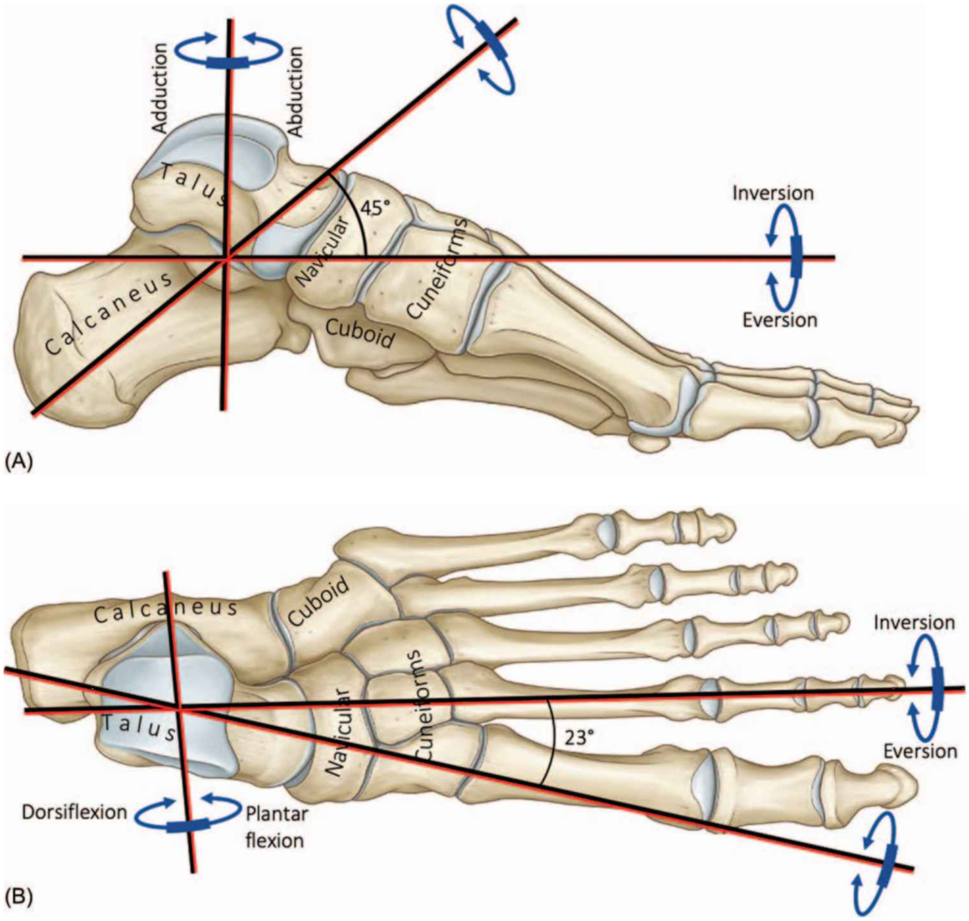

FIGURE 23.15 Movement axis of the subtalar joint; (A) medial view, (B) dorsal view.

42°−45° upward anteriorly from transvers plane and inclined medially 23° from longitudinal axis of the foot (Fig. 23.15) (Leardini et al., 2001; de Asla et al., 2006; Silvernail et al., 2015). There are always individual variations in orientation of subtalar join axis. Hence, inversion − eversion movements are larger when subtalar joint axis closer to the longitudinal axis of the foot. On the other hand, if the axis is closer to the vertical axis of the tibia, abduction − adduction movement become larger (Nawoczenski et al., 1998). Limited dorsi-plantar flexion movements also occur due to axis orientation (Leardini et al., 2001).

Subtalar joint transforms the rotational movements in lower extremity to the foot. Internal rotation of the tibia is transformed to the foot as a pronation, while external rotation of the tibia is transformed as supination to the foot. Because of oblique orientation of the subtalar joint axis, tibial movement almost lossless and each 1° transformed as 1° to the foot (Lundberg et al., 1989b). Pronation occurs as a combination of eversion − adduction − dorsiflexion, while supination occurs as a combination of inversion − adduction − plantar flexion. There is not any reliable measurement technique for subtalar range of motion, however, results of experimental studies show that range of motion is about 20° inversion and 10° eversion (Oatis, 2009; Wang et al., 2016).

Midtarsal joint

Midtarsal (transvers tarsal) joint is consisted of **talonavicular** and **calcaneocuboid** joints (Fig. 23.16). Talonavicular joint is an articulation between convex talar head and concave posterior facet of navicular (Oatis, 2009; Standring, 2016). Anterior talocalacaneal joint capsule covers this joint. Talonavicular ligament passes from dorsal side of the joint to further support stabilization. In addition, dorsal and plantar calcaneonavicular (spring ligament) ligaments (Fig. 23.17) are the most important ligaments that control the midtarsal joint. Particularly, the calcaneonavicular ligament has fibrocartilagineous joint surface and it acts as an important suspension for the head of the talus (Standring, 2016).

Calcaneocuboid joint is a saddle type structured joint between calcaneus and cuboid bones, which is wrapped up by connective capsule and surrounding ligaments (Oatis, 2009; Standring, 2016). This a part of lateral longitudinal

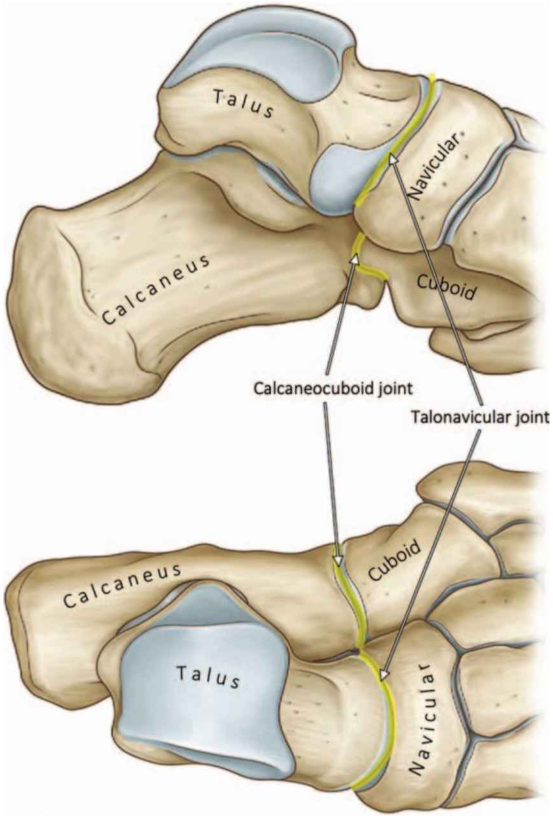

FIGURE 23.16 Midtarsal joint. *Adapted with permission from Elsevier, Drake et al. 2015.*

arch that transfer the body weight from calcaneus to lateral longitudinal arch. It has supported by the ligaments both plantar and dorsally. Bifurcate ligament, made up of dorsal calcaneonavicular and dorsal calcaneocuboid ligaments, supports the joint dorsally while short and long plantar ligaments are located plantar side (Fig. 23.18).

Movement at the midtarsal joint

Some researches indicated that talonavicular joint produced only 5° plantar flexion during 30° of plantar flexion of the ankle joint (Lundberg et al., 1989b; Oatis, 2009). It also resembles subtalar joint by means of supination and pronation movement, which occur with abduction/adduction and eversion/inversion. Because of these characteristics of talonavicular joint, it looks like subtalar joint (Savage-Elliott et al., 2013). Talonavicular and calcaneocuboid joints act as a unit with two axes. Longitudinal axis (Fig. 23.19) is similar with that of the subtalar joint and oblique axis corresponds with ankle joint (Fig. 23.20). From a cadaveric study, the range of pronation and supination motion had been measured 17° for the calcaneocuboid joint, 7.3° for the talonavicular joint. However, range of dorsiflexion had been measured 2.3° for calcaneocuboid joint and 7.0° for talonavicular joint (Ouzounian and Shereff, 1989). Combined range of motion at the midtarsal joint was found 22° around the oblique axis and 8° around the longitudinal axis (Hicks, 1953). However, a most recent in vivo study measured range of motion at foot joints using invasive markers, range of dorsi/plantar flexion and inversion/eversion were found 7.39° and 21.12° respectively (Wang et al., 2016). These movements at the calcaneocuboid joint were found 4.88° and 8.2° respectively. The motion axis of talonavicular and calcaneocuboid joints are parallel to each other in non-weight bearing conditions. Supination at the subtalar joint influence these motion axes and disarray their parallel positions which leads the midtarsal joint to lock (Loudon and Bell, 1996), which creates the rigid lever arm required in late stance of gait.

Distal intertarsal joints

The distal intertarsal joints are between the lateral cuneiform and cuboid bones along with the naviculocuneiform joints. In addition, the cuneiform bones formed a joint among themselves are in this group (Oatis, 2009; Standring, 2016). Motions of this joints are limited and allows just few degrees of pronation and supination to contribute foot movements (Fig. 23.21), (Hicks, 1953; Ouzounian and Shereff, 1989).

Tarsometatarsal and intermetatarsal joints

Distal tarsal bones articulate with proximal joint surfaces of metatarsal bones and form tarsometatarsal joints, and the transvers arch. They are reinforced by intertarsal, tarsometatarsal and intermetatarsal ligaments (Fig. 23.21) (Oatis, 2009; Standring, 2016). Tarsometatarsal joints, in another words Lisfranc's joint, transfers the load generated on the hindfoot to the forefoot during walking. The tarsometatarsal joints have a complex role in regulating joint pressures in the midfoot.

This occurs not only by individual joint action, but they act as a one unit. Load/surface ratio on these joints are relatively constant due to increased contact area of the joint under the increased load (Lakin et al., 2001), particularly during plantar flexion in late stance of gait. The bone alignment of the medial site of the foot together with strong ligaments makes this part of foot more rigid, which is very important property to maintain stability during running, hopping and walking activities.

Movement at tarsometatarsal joints

Tarsometatarsal joints have limited range of motion in sagittal plane, particularly in medial three joints have 1°–4° range of motion during dorsi-plantar flexion of the foot. The second tarsometatarsal joint is most limited in motion compared to others due to location of second

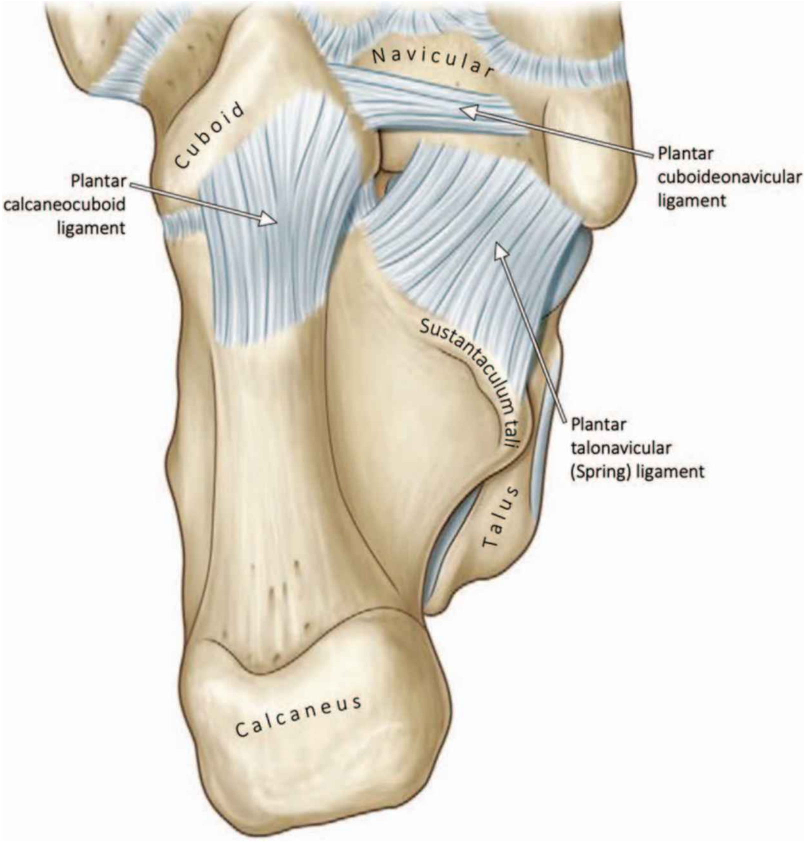
Navicular
Cuboid
Plantar calcaneocuboid ligament
Plantar cuboideonavicular ligament
Sustantaculum tali
Plantar talonavicular (Spring) ligament
Talus
Calcaneus

FIGURE 23.17 Plantar ligaments of the midtarsal joint. *Adapted with permission from Elsevier, Drake et al. 2015.*

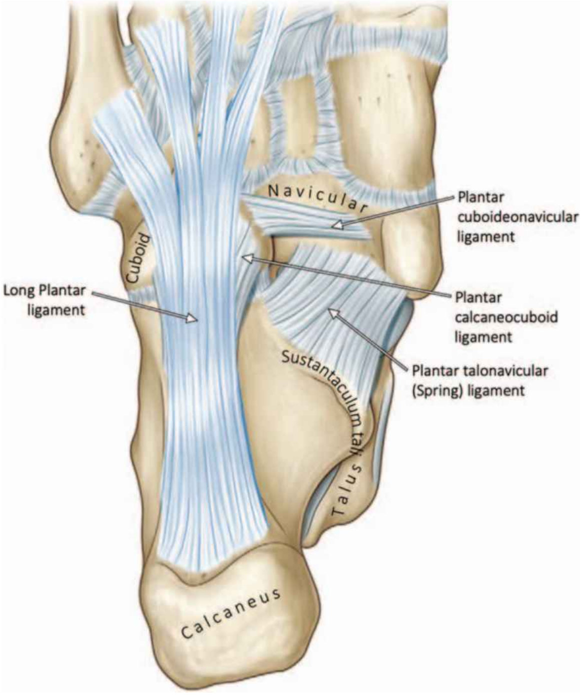
Navicular
Plantar cuboideonavicular ligament
Cuboid
Long Plantar ligament
Plantar calcaneocuboid ligament
Sustantaculum tali
Plantar talonavicular (Spring) ligament
Talus
Calcaneus

FIGURE 23.18 Plantar ligaments of the calcaneocuboid joint. *Adapted with permission from Elsevier, Drake et al. 2015.*

metatarsal bone between first and third cuneiform bones and first metatarsal (Lakin et al., 2001; Wang et al., 2016). Lateral third, fourth and fifth joints have relatively larger range of motion about 7°, 12° and 9° respectively (Ouzounian and Shereff, 1989; Glasoe et al., 1998; Yu et al., 2013). The foot adapted for effective bipedal walking but retaining some grasping adaptations. The first metatarsal moves plantar flexion – abduction – pronation while fifth metatarsal moves into plantar flexion – adduction – supination, which are analogous to hand grasping function (Holowka and Lieberman, 2018).

Metatarsophalangeal joints

The metatarsophalangeal joints consist of the metatarsal heads articulating with the proximal phalanges. Their structures are similar with the metacarpophalangeal joints of hand (Finney et al., 2018). These snovial joints covers by joint capsule, which is reinforced by collateral ligaments (Fig. 23.22A) and extensor tendons from dorsal side (Mueller, 2005). Metatarsophalangeal joints are supported by fibrous plantar plates (Fig. 23.22B), which contains type I, the same type and composition found in the meniscus in the knee and the annulus fibrosis of the intervertebral disk (Maas et al., 2016).

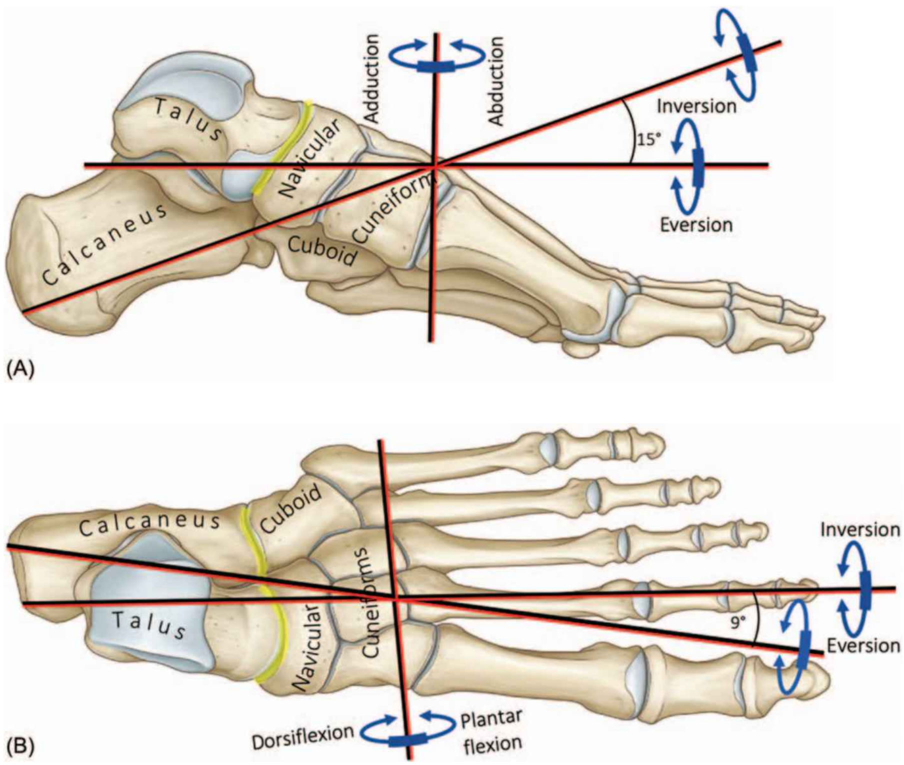

FIGURE 23.19 Longitudinal axis of the midtarsal joint; (A) medial view, (B) dorsal view.

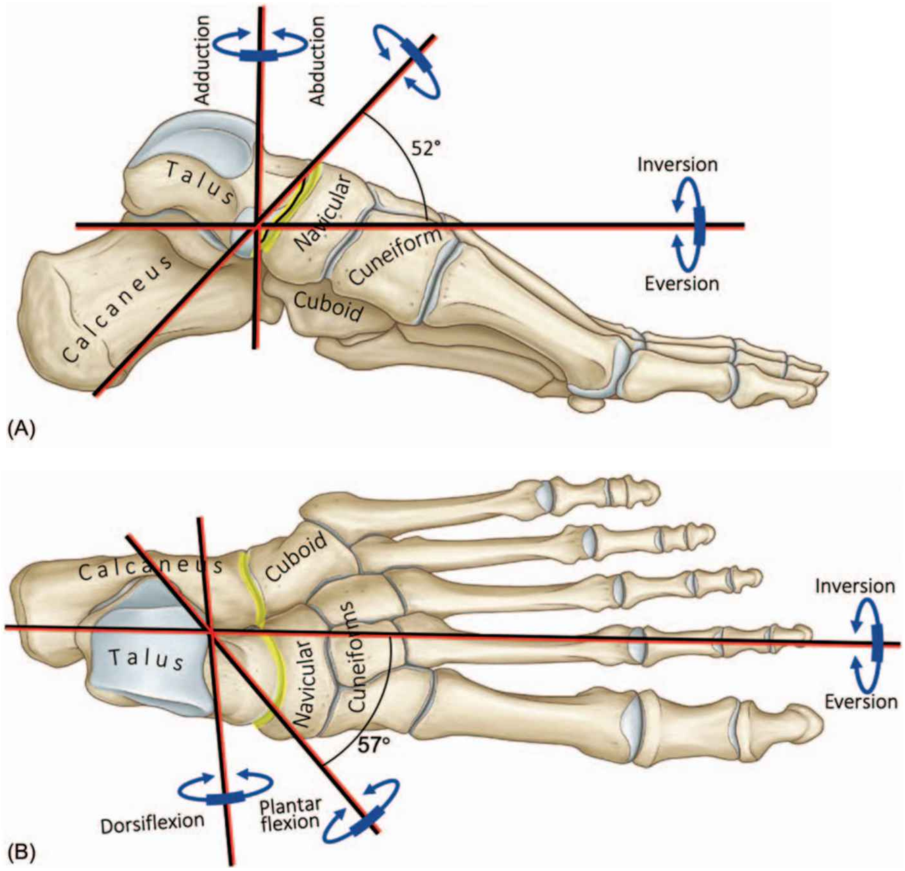

FIGURE 23.20 Oblique axis of the midtarsal joint; (A) medial view, (B) lateral view.

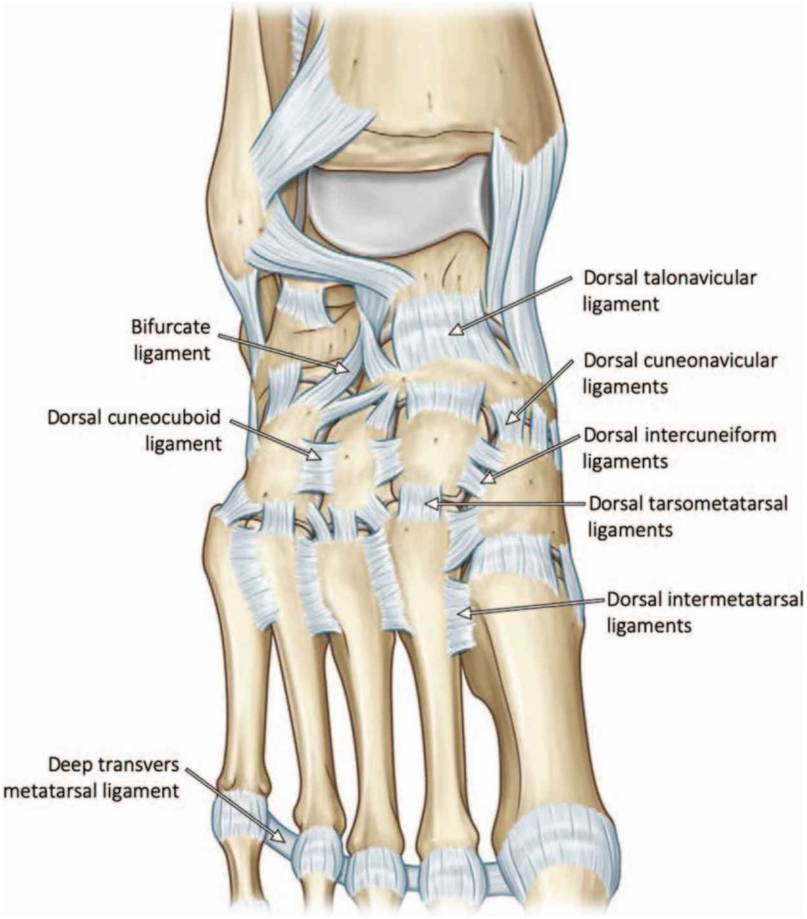
Dorsal talonavicular ligament
Bifurcate ligament
Dorsal cuneonavicular ligaments
Dorsal cuneocuboid ligament
Dorsal intercuneiform ligaments
Dorsal tarsometatarsal ligaments
Dorsal intermetatarsal ligaments
Deep transvers metatarsal ligament

FIGURE 23.21 Intertarsal, tarsometatarsal and intermetatarsal ligaments. *Reprinted with permission from Elsevier, Drake et al. 2015.*

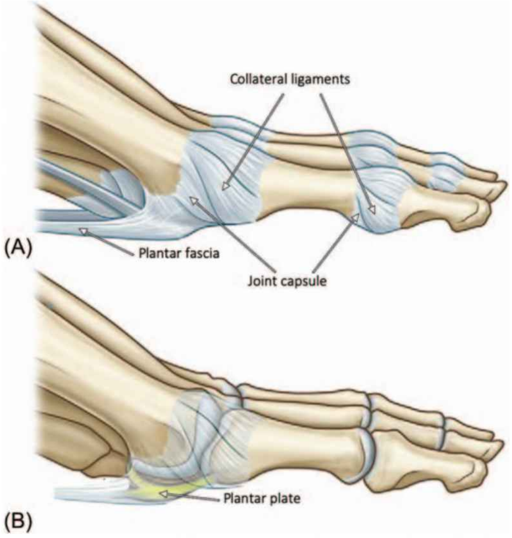

FIGURE 23.22 (A) Collateral ligaments of metatarsophalangeal and interphalangeal joints, (B) plantar plate beneath the metatarsal head. *Adapted with permission from Elsevier, Drake et al. 2015.*

Two sesamoid bones attached to the plantar plate and tendons of the flexor hallucis longus under the first metatarsal head have distinct mechanical function. These sesamoid bones protect the flexor hallucis longus tendon, and more significantly they increase length of moment arm of flexor hallucis brevis and functional range of extension of the first metatarsophalangeal joint required for push off phase of walking (Aper et al., 1994). When metatarsophalangeal joints are hyperextended specially at the end of the stance phase, distal metatarsal joint surfaces are exposed to direct stress. The fat pad of the metatarsal head moves with the plantar plate to cover the head of the metatarsal as a shock-absorbing cushion (Maas et al., 2016). Any toe deformity such as hammer or claw toes in a foot, these plates and fat pads slide distally and become unable to protect metatarsal joint surfaces. This can be seen in diabetic feet and other neurological diseases that affect the intrinsic plantar muscles.

Movement at metatarsphalangeal joints

These joints have two movement axis, primary movements are flexion and extension primarily on the sagittal plane. Slide abduction – adduction movement occur on transvers plane (Houglum and Bertoti, 2012). The range of hyperextension of the hallux is maximum between 55° and 96° of motion while plantar flexion is about 17°–34° (Shereff et al., 1986; Wrobel et al., 2004). The hyperextension movement is significant for roll-over mechanism at push off phase of walking and the range of motion is required between 40° and 90° to encourage this mechanism (Houglum and Bertoti, 2012).

Sesamoid bone resection leads shorter lever arm for flexor hallucis brevis and limit the range of extension required for push-up phase (Aper et al., 1994). In a normal condition, the first metatarsal head is elevated on the sesamoids during stance, but the sesamoids move during hallux dorsiflexion anterior to the metatarsal head and facilitates the first metatarsal plantar flexion about 10° that is essential for hallux dorsiflexion (Fig. 23.23) (Perera et al., 2011).

The most common disorder of the first metatarsophalangeal joint is hallux valgus. This is a progressive irreversible deformity (Kirkup et al., 1977; Glasoe et al., 2010), characterized with lateral deviation of the hallux at the metatarsophalangeal joint, medial deviation of the first metatarsal, and pronation of the hallux (Uchiyama et al., 2005). Forces created by ground reaction and muscles push the hallux into a valgus position result in a valgus deformity at the first metatarsophalangeal joint. Medial deviation of the first metatarsal head and ground reaction forces along with dynamic muscular forces eventually leads to weakening of the medial joint capsule and contractures of the lateral joint capsule and adductor tendons (Easley and Trnka, 2007). As a reaction, moment action of flexor hallucis longus muscle is changed from a plantar direction to a lateral direction and the resultant force pull of the flexor hallucis longus shifts, changing the joint moment action from the sagittal plane (Sanders et al., 1992; Glasoe et al., 2010). Flexor hallucis longus pulls sesamoid bone laterally, metatarsal head drops off the sesamoid apparatus and turns into pronation. As a result, extensor and flexor hallucis longus tendons bowstring laterally, further increasing the valgus (Welck and Al-Khudairi, 2018).

Interphalangeal joints

The interphalangeal joints of the toes is synovial joints. The hallux has only one IP joint connecting two phalanges, whereas the four lesser toes have two interphalangeal joints (proximal and distal interphalangeal joints) connecting three phalanges Interphalangeal articulations (proximal and distal interphalangeal joints) (Mueller, 2005; Standring, 2016). They are simple hinge-type joints which are supported by joint capsule, collateral ligaments and plantar cushion. Plantar cushion plays an important role to protect joint surfaces. The plantar flexion of proximal interphalangeal joints is less than 90° and dorsiflexion of the same joint is more than it. Plantar flexion motion is decreasing during motion toward lateral side. It is assumed that lateral second to fourth interphalangeal joints have some degree of hyperextension (Bowers et al., 1980; Husain et al., 2008).

Foot arches

The foot has two longitudinal arches and one transvers arch (Fig. 23.24). Medial longitudinal arch is consisted of the calcaneus, the talus, the navicular, the three cuneiforms (medial, intermediate and lateral), and the first, second and third metatarsals. Spring ligament (Fig. 23.17) supports the medial arch by quickly restoring the arch to its original condition when unloaded. The deltoid ligament and tendon of the tibialis posterior reinforces the medial longitudinal arch. The arch is further supported by the plantar aponeurosis, by the tendons of the tibialis anterior and posterior, and peroneus longus, flexor digitorum longus and flexor hallucis longus (Mueller, 2005; Kapandji, 2011; Houglum and Bertoti, 2012).

The calcaneus forms the lateral longitudinal arch together with the cuboid, fourth and fifth metatarsal bones. The long plantar and the plantar calcaneocuboid ligaments and the extensor tendons alongside with the tendon of peroneal muscles, and short muscles of the fifth toe support the lateral longitudinal arch.

The transvers arch is formed by of the three cuneiforms, the cuboid, and the five metatarsal bases and

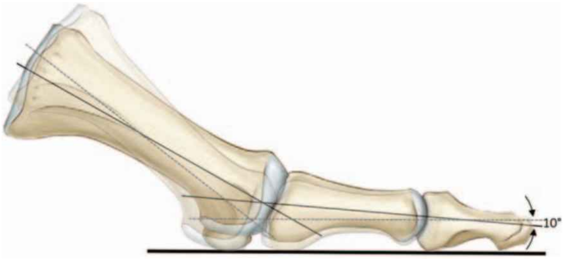

FIGURE 23.23 Sesamoid bones under the first metatarsal head increases the range of metatarsophalangeal joint extension.

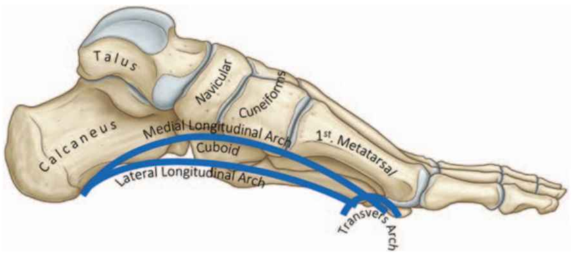

FIGURE 23.24 Medial longitudinal arch, lateral longitudinal arch, and transvers arch. *Reprinted with permission from Elsevier, Drake et al. 2015.*

continues to metatarsal heads. Transverse arches are supported by the interosseous, plantar, and dorsal ligaments, and the short muscles of the first and fifth toes particularly the transverse head of the adductor hallucis muscle at the distal part. The peroneus longus tendon also reinforces lateral longitudinal arch and medial longitudinal arch as well as proximal part of the transvers arch (Sun et al., 2012).

The osseous compression load-bearing elements serve to supply the structural framework of the longitudinal arch. The talus and calcaneus form the rearfoot, and the navicular, cuboid, cuneiform and metatarsals form the forefoot. During weight bearing conditions, the height of the medial longitudinal arch is reduced with the rearfoot plantarflexion and forefoot dorsiflexion. When the foot is unloaded in close kinetic chain medial longitudinal arch height increases to its normal value as rear foot moves into dorsiflexion and forefoot moves to plantar flexion (Xiong et al., 2010).

When chimps walk bipedally, midfoot breaks down because of absence of crucial medial longitudinal arch and rigid lever system during the late stance. This implies a weaker plantar aponeurosis and hence greater demand on muscular effort to resist forces acting on the toes during late stance (McKeon et al., 2015). In the human foot, the plantar fascia can resists 1000 −1500 N tensional force (Ward et al., 2003), and has been found to be the strongest contributor to support the longitudinal arches in static and dynamic conditions (Fig. 23.25) (Angin et al., 2018). Dissimilar to those of in chimps feet, intrinsic and extrinsic muscles of the human foot work as tandem for tuning the tensional force on the plantar fascia (Kirby, 2017). The plantar fascia starts from calcaneus and travels to anterior of the foot as divided to five parts. Each part is attached to the metatarsal heads and phalanges as well as blended with the tendon sheath of the toe flexor muscles and transvers metatarsal ligaments (Standring, 2016). It has been revealed that the plantar fascia is a continued part of Achilles tendon under the foot, hence, excessive stretching and tightness of the Achilles tendon are thought to be the risk factors of plantar fasciitis (Cheung et al., 2006). As Achilles tendon and plantar fascia relationship is still under debate, Stecco et al. (2013) indicated that, from a morphological point of view, a connection between the Achilles tendon and the PF is more likely in younger people. From the anatomical point of view, whether there is direct connection between two structure, or not, calcaneus forced to be in plantar flexion and reduces medial longitudinal arch height such as seen in the pes planus foot (Mahan and Flanigan, 2001; Kirby, 2017), and this increases the tensional stress at the calcaneal-plantar fascia junction that may result in enthesitis.

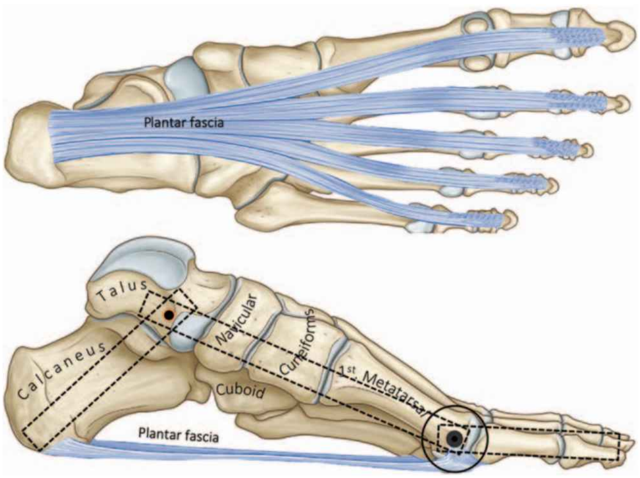

FIGURE 23.25 Plantar fascia and windlass mechanism.

Individual with increased longitudinal arch height or pes cavus often prone to abnormal weight bearing stresses, foot and ankle instability, restricted foot mobility, and shoe fitting difficulty (Smith and Green, 2001). Furthermore, it has been indicated that the individuals with pes cavus were more likely to have lateral ankle sprains and iliotibial band friction syndrome while with pes planus were more likely to have knee pain (Williams et al., 2001). It has also been found that foot pain is a common in pes cavus and occured more often compared to normal arched foot (Burns et al., 2005).

During the gait, the height of the medial longitudinal arch is relatively reduced until end of the loading response as ground reaction force passes from lateral side of the subtalar motion centre that results with pronation of the subtalar joint and internal rotation of the tibia. This must be a physiological response of the foot when it is loaded in a dynamic condition. The foot in this stage is flexible and this flexibility provides high adaptive capacity to the foot on uneven surfaces.

Following the loading response, foot is required to behave as semirigid structure to maintain medial longitudinal arch structure under the load of body weight while absorbing ground reaction forces and stores mechanical energy. During the terminal stance (push-off phase), foot became a rigid lever arm to raise and move the body weight forward. Three mechanism work in tandem to provide this very distinct specification in the human foot: i) Lower extremity turns to external rotation. This movement is transmitted to the foot via subtalar joint as supination and midtarsal joint is locked. ii) When the tibia rotate forward over the talus, ankle dorsiflexion is initiated. After heel rise, the ankle joint moves back into plantar flexion, forcing the metatarsophalangeal joints to dorsiflexion. Since the plantar fascia attached around the metatarsal heads, a "windlass" effect (Fig. 23.26) takes place which increases tension across the longitudinal arch,

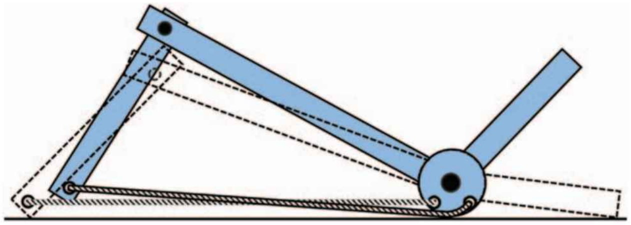

FIGURE 23.26 Windlass mechanism; extension of the metatarsophalangeal joint, increases tension on the plantar fascia and elevates medial longitudinal arch. *Reprinted with permission from Istanbul Tıp Kitabevleri, Angın, 2016.*

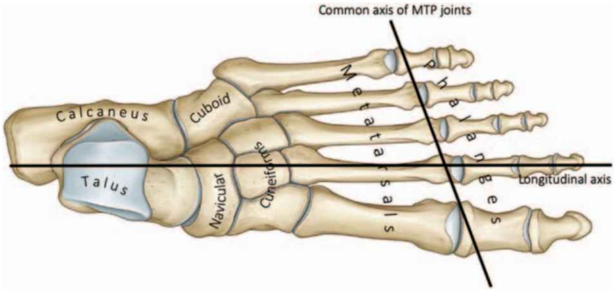

FIGURE 23.27 Common axis of MTP joints is not perpendicular to the longitudinal axis of the foot. *Reprinted with permission from Elsevier, Drake et al. 2015.*

further elevates the arch and increases foot stability. iii) Since common axis of the metatarsophalangeal joints is positioned as oblique to the longitudinal axis of the foot (Fig. 23.27), medial side of the foot raise higher than the lateral side of the foot, that provides supination with further stability (Kapandji, 2011).

Muscles of the ankle and foot

Origin of Extrinsic muscles of the ankle and the foot are always outside of the foot, while their tendons are inserted to structures in the foot (there is no muscle attachment on the talus).

Anterior muscles

Dorsiflexor muscles tibialis anterior, extensor digitorum longus, extensor hallucis longus, and peroneus tertius are localized anteriorly to the ankle joint axis (Fig. 23.28). One of the two main functions of the dorsiflexor muscles is clearing the foot from surface in swing phase of walking. Second function begins with stance phase, following the heel strike dorsiflexor muscle activity turn to eccentric contraction controlling the ankle plantar flexion and preventing the foot from rapid strike to the ground following heel strike. Eccentric contraction of the dorsiflexors also provide ground reaction force absorption.

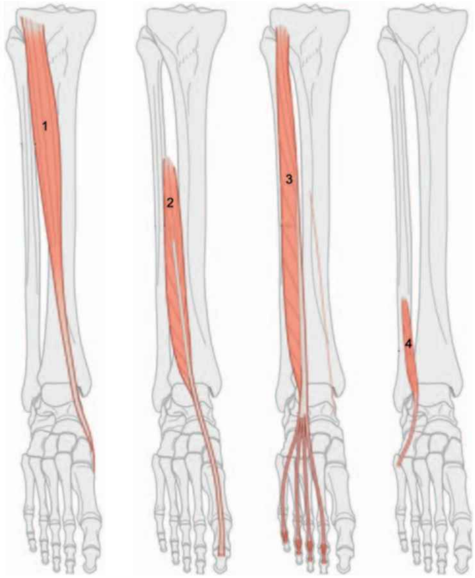

FIGURE 23.28 Anterior extrinsic muscles; 1) Tibialis anterior, 2) Extensor digitorum longus, 3) Extensor hallucis longus, 4) Peroneus tertius. *Reprinted with permission from Elsevier, Drake et al. 2015.*

Tibialis anterior

Tibialis Anterior is the largest and strongest dorsiflexor, and its anatomical cross-sectional area is larger than the sum of all other dorsiflexors. As a prime dorsiflexor of the ankle joint, it keeps the foot clear from the floor in swing phase and provide controlled plantar flexion for smooth foot contact just after the heel strike. From the loading response to midstance, eccentric contraction in tibialis anterior is changed to concentric contraction to pull the tibia over the talus for full weight bearing in the single stance. Moment arm of the tibialis anterior muscle is approximately 35–60 mm for dorsiflexion (Rugg et al., 1990; Menegaldo et al., 2004), and 10 mm for inversion movement as it passes medial to the subtalar joint (Lee and Piazza, 2008). Therefore, tibialis anterior muscle also moves the foot into supination and inversion, that prevents the subtalar joint from excessive pronation. However, its invertor moment arm is shorter than the other invertor muscles tibialis posterior and flexor hallucis longus (Lee and Piazza, 2008).

Various pathologic conditions may affect the tibialis anterior function. Weakness may lead uncontrolled foot drop during initial stance, or difficulty in clearance of the foot from the ground during swing phase. Peroneal muscles pull the subtalar joint into pronation and foot may turn to abduction.

Extensor hallucis longus

Extensor hallucis longus is only extensor of the first metatarsophalangeal joint and lies between tibialis anterior and extensor digitorum longus. It originates from the middle half of the medial surface of the fibula, and from the anterior surface of the interosseous membrane. Its tendon inserted on to the basis of the distal phalanx of the hallux (Mueller, 2005; Standring, 2016). As its tendon crosses ankle and subtalar joints, the moment arm of extensor hallucis longus on the sagittal plane is about 40–50 mm, it creates additional dorsiflexion moment for ankle joint. However, moment arm on frontal plan is negligibly short to create inversion moment (McCullough et al., 2011). Exerted force by extensor hallucis longus was measured 8.7 kg (Aper et al., 1994). Weakness of the extensor hallucis longus is a common indicator for L4-5 S1 disk degeneration. Distal phalanx extension test is widely used in a clinical setting to diagnose whether there is a motor loss caused by L5-S1 nerve root compression (Young et al., 1983).

Extensor digitorum longus

Extensor digitorum longus originates from multiple structures such as lateral tibial condyle, medial surface of the fibula, interosseous membrane and deep fascia. Its tendon divides into four slips and are attached to the second, third, fourth and fifth toes forming dorsal digital expansions on the dorsal aspects of the proximal phalanges. The expansion approaches a proximal interphalangeal joint, and divides into three slips. The central slip attached to the base of the middle phalanx, two collateral slips merge on the dorsum of the middle phalanx and attached to the base of the distal phalanx (Standring, 2016).

Extensor Digitorum Longus is larger than the extensor hallucis longus, and half of the tibialis anterior, it is prime extensor of the lateral four metatarsophalangeal joint. extensor hallucis longus acts with tibialis anterior and fibularis tertius, as a dorsiflexor of the ankle. Together with extensor hallucis longus, tighten the plantar aponeurosis (Oatis, 2009; Standring, 2016). As the tendon of the extensor digitorum longus crosses subtalar joint laterally it creates inversion moment on the foot.

Peroneus tertius is the most lateral dorsiflexor muscle, which works tandem with other dorsiflexor muscles and helps ankle dorsiflexion. Moment arm of this muscle also creates eversion (Oatis, 2009).

Posterior muscles

Gastrocnemius, soleus and plantaris muscles (called Triceps Surae) are superficial extrinsic plantar flexors of the ankle joint (Fig. 23.29). These muscles provide 60–87% of the total plantar flexor torque (Oatis, 2009; Bogacka et al., 2017). Gastrocnemius and soleus attached to the posterior side of the calcaneus via Achilles tendon. Long tendon of the plantaris muscle travels distally medial side of the Achilles tendon and is attached to calcaneus. Deep group muscles are tibialis posterior, flexor digitorum longus and flexor hallucis longus and lies beneath the gastrocnemius and soleus muscles (Fig. 23.29).

Gastrocnemius

Gastrocnemius muscle originates from the femoral condyles and attaches to the posterior calcaneus via Achilles tendon. It is the prime plantar flexor of the ankle joint. As Achilles tendon has 48–64 mm plantar flexor moment arm (Klein et al., 1996; McCullough et al., 2011), this is

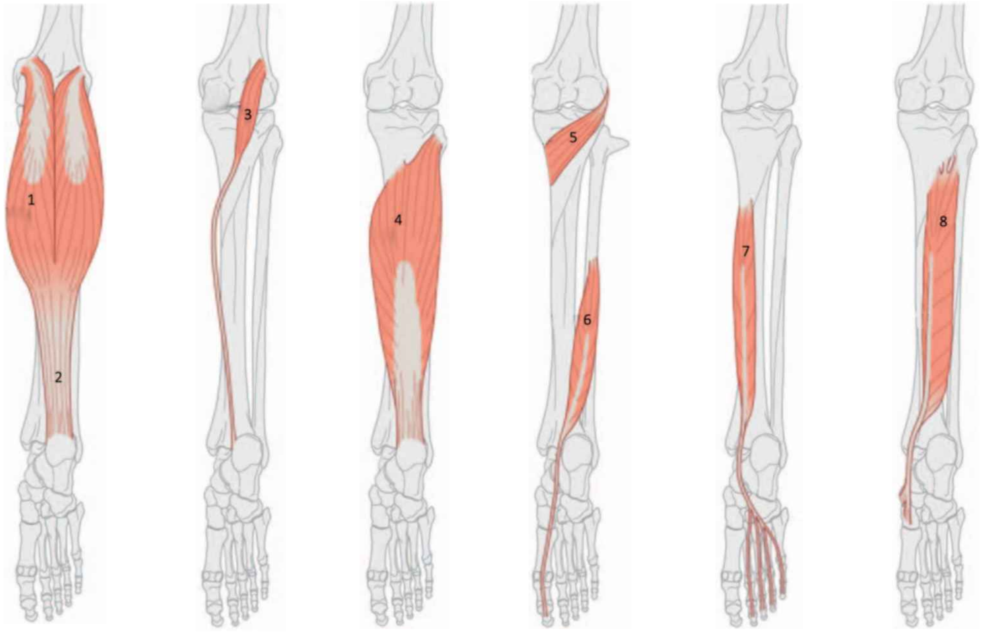

FIGURE 23.29 Posterior extrinsic muscles; 1) Gastrocnemius, 2) Achilles tendon, 3) Plantaris, 4) Soleus, 5) Popliteus 6) Flexor hallucis longus, 7) Flexor digitorum longus, 8) Tibialis posterior. *Reprinted with permission from Elsevier, Drake et al. 2015.*

necessary not only for raising on tiptoe but, for also propulsion of the body weight during the push-off phase of the gait. Gastrocnemius begin to act eccentrically during early stance, midstance and beyond until heel-off the ground for controlled roll-over of the foot. Eccentric contraction is transformed to concentric contraction during the terminal stance.

Gastrocnemius muscle also creates flexor moment on the knee joint. Length of the moment arm reaches 30 mm with knee is in 90° flexion (Klein et al., 1996). Plantar flexor moment created by gastrocnemius partially depends on the position of the knee joint. With knee flexed position, gastrocnemius cannot exerts maximum force, therefore raising over the metatarsal heads is required this muscle work with soleus as one unit.

Weakness of the gastrocnemius results in calcaneal gait, which foot sole may not contact to surface during walking. If one has weak gastrocnemius, he/she could face difficulty on climbing stair and uphill walking. Along with the Achilles tendon, gastrocnemius muscle often shows shortness or contractures that limits the required dorsiflexion, and stance phase begins with the foot, therefore, roll-over mechanism is eliminated during walking. When foot with short gastrocnemius loaded, forefoot-hindfoot alignment may be disturbed, and tight Achilles tendon pulls the posterior calcaneus upward, hence calcaneus became plantar flexed position and medial longitudinal arch may be disappeared. Midfoot collapses, and Achilles tendon pulls the calcaneus into valgus or varus position.

Soleus

Soleus is a large, flat muscle lies beneath (anterior) the gastrocnemius. It originates from fibular head and proximal fibula; the middle medial border of the tibia; and from a fibrous band between the tibia and fibula. Its tendon joins to gastrocnemius tendon and form the Achilles tendon (Cohen, 2009; Oatis, 2009). Soleus produces nearly 30% of the strength of all extrinsic muscle of the ankle and foot, while gastrocnemius produces only 20% of those of total strength (Silver et al., 1985), suggesting that the power of plantar flexion generated primarily by the soleus and not by the gastrocnemius (Cohen, 2009). It has been suggested that pulling directions of medial and lateral heads of the gastrocnemius muscle and the soleus muscle are differ at the musculotendinous junction of the Achilles tendon may produce friction between fibers. These inhomogeneous loads on different fibers have been suggested as a possible underlying mechanism for tendon injury (Arndt et al., 1999; Cohen, 2009).

Plantaris

The plantaris muscle originates from the lateral supracondylar line of the femur (Olewnik et al., 2018). Together with the gastrocnemius, and soleus, they are collectively named as the triceps surae muscle. In many mammals, plantaris is well developed however, the muscle is absent in 7–20% of limbs in humans. Normally, its calcaneal insertion may varies, attachment independently of the Achilles tendon is a common form (Spina, 2007; Olewnik et al., 2018). The mechanical point of view, it is almost non-functional, but it is found to be an important muscle for the proprioceptive sense carrying to the central nervous system (Nazeer Ahmed et al., 2017).

Plantaris muscle crosses knee and ankle joints which makes it prone to rupture. Dorsiflexion of the ankle with knee in full extension, which results in simultaneous active contraction and passive stretching of the muscle may cause rupture (Rohilla et al., 2013). It is very common in tennis players, however, a recent study has revealed that gastrocnemius muscle injury is more common in tennis leg (Harwin and Richardson, 2016)

Deep group muscles are tibialis posterior, flexor digitorum longus and flexor hallucis longus and lies beneath the gastrocnemius and soleus muscles.

Tibialis posterior

Tibialis posterior is a deep muscle made posterior deep group of muscles collectively with flexor digitorum longus and flexor hallucis longus. It originates from the posterior proximal tibia, continues along the posterior and medial aspect of the tibia. Its tendon proceeds behind the medial malleolus to insert on the navicular, the middle three metatarsal bases and cuneiforms (Deland and Hamilton, 2008; Semple et al., 2009; Standring, 2016). The tendon crosses around the medial malleolus constitutes a 30 mm moment arm on the subtalar joint, tree times longer than that of tibialis anterior (Deland and Hamilton, 2008). Because of this longer moment arm, the posterior tibial tendon has the greatest mechanical advantage to invert the foot and lock the triple joint complex (Deland and Hamilton, 2008; Oatis, 2009). Therefore, it is one of the greatest contributors as a contractile tissue for ability of the foot to become a rigid lever for push-off. Plantar flexion moment arm is measured about 10 mm at the neutral position of the ankle joint, however, it reduces closer to null in full plantar flexion position (Spoor et al., 1990).

The tibialis posterior muscle has a vital role during gait; via multiple insertion points into the tarsal bones it acts as the primary dynamic stabilizer of the rearfoot and medial longitudinal arch (Semple et al., 2009; Kamiya et al., 2012). Weakness of the tibialis posterior muscle is a main cause of acquired flatfoot. The posterior tibial tendon insufficiency caused by increase in friction between tendon and malleolar bone may also results in flatfoot (Kamiya et al., 2012). Intact peroneal muscles pull the foot further eversion and aggravate footflat. Spasticity of tibialis posterior as well as weakness of peroneal muscles lead increased plantar flexion and inversion referred to pes varus or pes equinovarus deformity (Root, 1984; Picelli et al., 2017).

Flexor digitorum longus

Flexor digitorum longus originates from the posterior surface of the tibia and the fascia covering tibialis posterior. Its tendon passes behind the medial malleolus where it shares a groove with tibialis posterior, passes forwards as four separate tendons, each passes between the slips of the corresponding tendon of flexor digitorum brevis at the base of the proximal phalanx, and attached to the plantar surfaces of the bases of their distal phalanges (Standring, 2016). These four tendons also provide origins for lumbrical muscles.

In open kinetic system, flexor digitorum longus pulls lateral four toes into flexion while stabilizing these toes against ground reaction force in closed kinetic chain. Flexor digitorum longus muscle has inversion moment arm as 75% as that of tibialis posterior muscle, and greater work exerted in foot with pes planus (Angin et al., 2018). Indeed, hypertrophy of flexor digitorum longus has been noted on Magnetic Resonance Image in cases of pes planus that are associated with posterior tibial tendon insufficiency (Wacker et al., 2003).

Weak flexor digitorum longus muscle is unable to provide required torque for resisting to ground reaction force, which causes delayed heel off. Increased stiffness or contracture of the flexor digitorum longus limit dorsiflexion of distal interphalangeal joints, may results in claw toe, hammer toe and mallet toe deformity (Standring, 2016).

Flexor hallucis longus

Flexor hallucis longus originates from the distal two-thirds of the posterior surface of the fibula, interosseous membrane and from the fascia covering tibialis posterior. Its tendon passes the posterior surface of the talus and the inferior surface of the sustentaculum tali. Its tendon travels anteriorly and crosses the tendon of flexor digitorum longus (Knot of Henry) and travels the medial side of the sole towards the big toe. Further, the tendon lies between two sesamoid bones beneath the head of the first metatarsal (Kirane et al., 2008a,b). As its tendon enters the big toe and inserts onto the base of its distal phalanx, flexor hallucis longus is the prime flexor of the hallux and only the flexor of interphalangeal joint (Standring, 2016).

Total force exerted by flexor hallucis longus was experimentally measured 20.1 kg (Aper et al., 1994). Flexor hallucis longus, with the length of 25 mm moment arm also works as a plantar flexor for ankle joint. Effect of the flexor hallucis longus muscle on subtalar joint is limited as its moment arm for inversion is found to be 7 mm (Klein et al., 1996). As dorsiflexion and eversion moments are maximal in late stance, the flexor hallucis longus contracts producing counteracting plantarflexion and inversion moments. Thus, the flexor hallucis longus helps to stabilize the great toe and support the medial longitudinal arch of the foot (Kirane et al., 2008a,b). In a study of dynamic walking simulation, it has been observed much smaller range of flexor hallucis longus excursion, which refers to isometric or near-isometric flexor hallucis longus function (Kirane et al., 2008a,b). During push-off phase, tendon excursion occurs with ankle plantar flexion, however the excursion neutralized due to dorsiflexion of the hallux. These two simultaneous and opposite movements (Fujita, 1985; Leardini et al., 1999c) provide isometric contraction of flexor hallucis longus during late stance of the gait and transfers energy from one joint to the other as suggested for multiarticular muscles (Kaya et al., 2005).

Flexor hallucis longus has greater effect on running and jumping. Particularly tiptoe standing causes flexor hallucis longus injury such as tendinitis and partial rupture of the muscle belly in ballet dancers (Howard, 2000). Flexor hallucis longus weakness may result in decreased plantar flexion and inversion moments, while shortness or contracture lead dorsiflexion limitation on hallux that depends on position of the ankle joint.

Lateral group muscles

Lateral extrinsic muscle group consists of peroneus longus and peroneus brevis muscle and reside lateral side of the leg (Fig. 23.30). Peroneal muscles reside on lateral side of the leg, and prime evertors of the foot. Of the 65% total evertor moment produced by peroneal muscles. Peroneus longus and brevis are innervated by superficial peroneal nerve (L5, S1-2)

Peroneus longus

Peroneus Longus muscle originates from the head and proximal two-thirds of the lateral surface of the fibula, the deep surface of the deep fascia, the anterior and posterior intermuscular septa, and rarely from the lateral condyle of the tibia. The tendon enters the plantar region and inserts into the base of first metatarsal bone and medial cuneiform bone (Standring, 2016; Bogacka et al., 2017). With its 10–30 mm pronator moment arm, peroneus Longus is the prime evertor of the foot and work with Peroneus brevis (Oatis, 2009). The tendon passes posteriorly to the lateral malleolus and provide with 10 mm plantar flexor moment arm which also enables peroneus longus to act as secondary plantar flexors (Klein et al., 1996; Sarig-Bahat et al., 2013). The peroneus longus and peroneus brevis as a group of peroneal muscles generate only 4% of strength (Bogacka et al., 2017). In practice, the most important function of the peroneus Longus muscle is to depress or to hold stable the

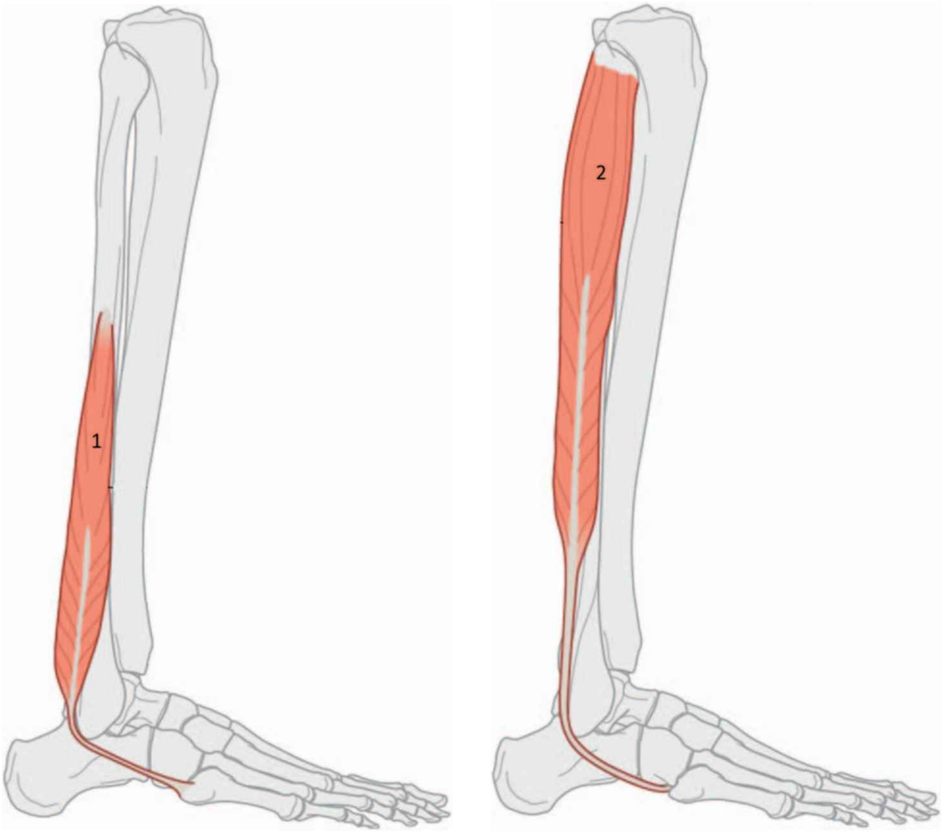

FIGURE 23.30 Lateral extrinsic muscles; 1) Peroneus brevis, 2) Peroneus longus. *Reprinted with permission from Elsevier, Drake et al. 2015.*

first ray of the foot in the toe-off phase of gait, to stabilize the ankle joint and support the architecture of the foot (Standring, 2016; Bogacka et al., 2017).

The ankle is protected from lateral sprains when the ankle joint is in inversion through a dynamic defense mechanism that activates a peroneal eversion response induced by the proprioceptive input of the inversion moment. The peroneus longus is normally activated during the middle and terminal stance phases of the stride, providing lateral support during the single limb stance (Santilli et al., 2005).

Most dramatic result of the peroneal muscles weakness is lateral ankle sprain (Rottigni and Hopper, 1991). Raising on the toes may be difficult due to instability of the first tetatarsal bone (Root, 1984). If weakness of peroneus longus is combined with tibialis anterior weakness, more serious problem such as pes varus or pes cavus deformity occurs in the foot (Maynou et al., 2017). The peroneus longus contracture and spasticity combined with spastic gastrocnemius may lead pes equinovalgus deformity particularly in young children with hemiparesis (Vinti et al., 2018).

Peroneus brevis

Peroneus brevis originates from the distal two-thirds of the lateral surface of the fibula, anterior to peroneus longus, and from the anterior and posterior intermuscular septa. The tendon passes behind the lateral malleolus together with tendon of peroneus longus. The tendon of peroneus brevis extends forwards on the lateral side of the calcaneus above the fibular trochlea and is inserted into the base of the fifth metatarsal (Standring, 2016). peroneus brevis muscle with multiple moment arms, 15 mm for plantar flexion, 22 mm for external rotation and 20 mm for pronation, obviously acts as a triplanar actuator for the foot and ankle complex (McCullough et al., 2011). The peroneus brevis may limit inversion of the foot and so reduce strain on the lateral part of interosseous, talocalcaneal, lateral talocalcaneal and calcaneofibular ligaments that are tightened by this movement (Standring, 2016). Cross-sectional area of both peroneus longus and peroneus brevis has found to be reduced in lateral ankle sprain, this refers to the peroneal group of muscles could not provide required eversion moment (Lobo et al., 2016). Similar result has also been found in people with pes planus (Angin et al., 2014).

Plantar intrinsic muscles

Intrinsic muscles originate and insert within the foot. These muscles generally have small moment arms, small cross-sectional areas, and serve primarily to stabilize the arches, more likely provide stabile base for muscles of

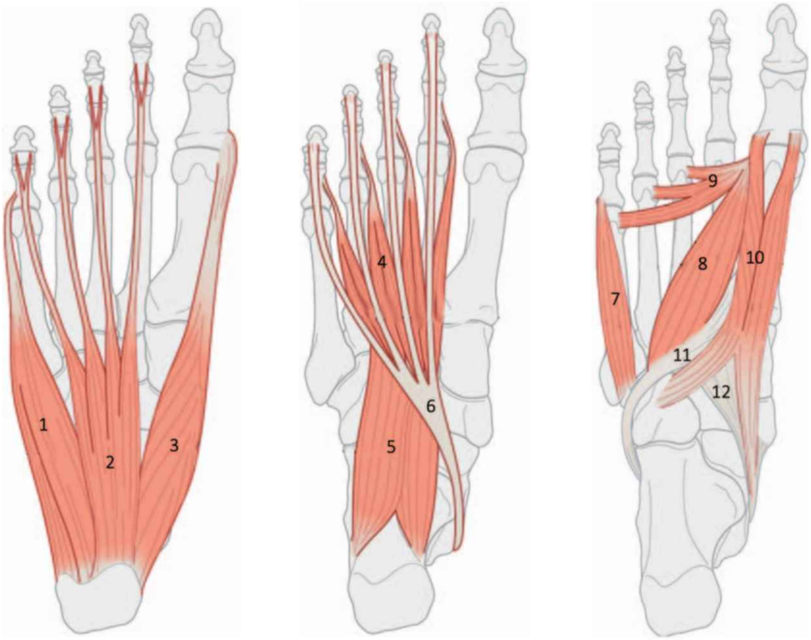

FIGURE 23.31 Plantar intrinsic muscles; 1) Abductor digiti minimi, 2) Flexor digitorum brevis, 3) Abductor hallucis, 4) Lumbrical muscles, 5) Quadratus plantae, 6) Flexor digitorum longus tendon, 7) Fexor digit minimi brevis, 8) Adductor hallucis obliques, 9) Adductor hallucis transversus, 10) Flexor hallucis brevis, 11) Peroneus longus tendon, 12) Tibialis posterior tendon. *(Adapted with permission from Elsevier), (Drake et al., 2015).*

prime movers (Cameron et al., 2008; McKeon et al., 2015). The intrinsic muscles of the foot work as a functional unit in order to dynamically stabilize and assist in the support of the medial longitudinal arch. When they are not functioning properly, the foot becomes unstable and malaligned. This may manifest in foot-related problems (Kirby, 2017). Overall weakness of the plantar intrinsic muscles lead pes cavus, hammer toe and claw toe deformities (Fig. 23.31).

Abductor hallucis

The abductor hallucis muscle is the most medial intrinsic muscle of the plantar surface of the foot. It originates from the medial calcaneal tuberosity and inserts the proximal phalanx with or without attachment onto the medial sesamoid bone (Standring, 2016). As the tendon lies inferior to the transverse axis of the first metatarsophalangeal joint, abductor hallucis performs abduction and plantar flexion of the hallux (Brenner, 1999). abductor hallucis is active in the late stance and toe-off phases of gait (Reeser et al., 1983) and is a dynamic stabilizer of the longitudinal arch (Wong, 2007). Total force exerted by abductor hallucis was experimentally measured 29.2 kg (Aper et al., 1994). Cross-sectional area has been found to be reduced in foot with pes planus (Angin et al., 2014). Atrophy in the abductor hallucis muscle fiber has also been detected in the foot with hallux valgus (Hoffmeyer et al., 1988).

Flexor hallucis brevis

It originates as two divisions from medial plantar surface of the cuboid bone, lateral cuneiform, tendon of tibialis posterior and medial intermuscular septum. The twin tendons are attached to the sides of the base of the proximal phalanx of the great toe. The medial part blends with the tendon of abductor hallucis, and that of adductor hallucis. Both tendons cover sesamoid bones beneath the first metatarsal head (Standring, 2016).

Sesamoid bones play important role as they increase moment arms of both medial and lateral tendon of flexor hallucis brevis muscle, which is required during late stance to keep the hallux firmly on the ground when body weight transferred over the forefoot. Although, there is not enough knowledge about the type of contraction in dynamic condition, extension of the hallux driven by ground reaction force needs eccentric contraction of the flexor hallucis brevis during late stance just until the late push-up phase that metatarsophalangeal joints move into flexion. Total force exerted by flexor hallucis brevis was experimentally measured 21.5 kg (Aper et al., 1994).

Weakness of the flexor hallucis brevis results in extension in the first metatarsophalangeal joint and flexion in interphalangeal joint of hallux when flexor hallucis longus is intact. Stability of the first metatarsophalangeal joint and medial longitudinal arch may be disturbed. It has also been shown that flexor hallucis brevis one of the important contributors of the medial longitudinal arch support. Hence, cross-sectional area of the flexor hallucis brevis muscle reduced in foot with severe pes planus (Angin et al., 2014).

Flexor digitorum brevis

It originates from medial calcaneal tubercle, middle part of plantar aponeurosis and intermuscular septum. Muscle continues as four tendinous structures at the level of tarsometatarsal joints, which perforated by flexor digitorum longus tendons at their end, and each attach to the basis of proximal phalanges of the lateral four toes. Primary function of the flexor digitorum brevis muscle is flexion of corresponding metatarsophalangeal joints (Oatis, 2009; Standring, 2016). during walking. On the other hand most recent study revealed that flexor digitorum brevis muscle activity increases during up-hill walking, and stair climbing and stepping down (Riddick et al., 2019). Weakness of this muscle may affect these activities as well as stability of the lateral four metatarsophalangeal joints in late stance.

Quadratus plantae

Medial head of quadratus plantae originates from medial concave surface of the calcaneus. Lateral head of quadratus plantae originates from latero-distal process of the calcaneal tuberosity and from the long plantar ligament. It attaches lateral border of the flexor digitorum longus tendon (Oatis, 2009). The function of the quadratus plantae muscle (with contribution of the lumbrical muscles) is fine tuning of the pulling direction of the flexor digitorum longus. As the flexor digitorum longus enters the foot from its medial aspect, its action pulls the toes medially. The pull of the quadratus plantae on the tendons of the flexor digitorum longus redirects the force on the toes, producing flexion of the toes in the sagittal plane (Fig. 23.32).

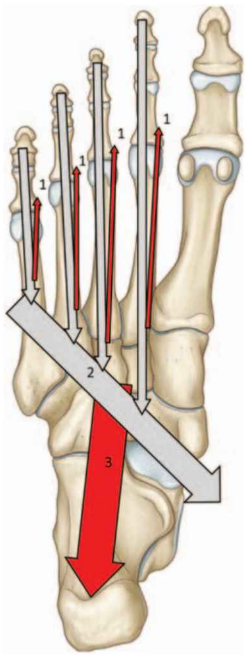

FIGURE 23.32 Mechanical interaction between (1) Lumbrical muscles, (2) Flexor digitorum longus, and (3) Quadratus plantae. *Adapted with permission from Elsevier and İstanbul Tıp Kitabevleri, Drake et al., 2015; Angın, 2016.*

Abductor digiti minimi and flexor digiti minimi brevis

Abductor digiti minimi originates from calcaneal tubercle, lateral region of the plantar aponeurosis and intermuscular septum. Its tendon attaches to lateral basis of the proximal phalanx of the fifth toe. This muscle provides limited flexion and abduction movements on the fifth metatarsophalangeal joint (Oatis, 2009; Standring, 2016).

Flexor digiti minimi brevis originates from the medial plantar surface of the base of the fifth metatarsal, and from the sheath of fibularis longus. It has a distal tendon that inserts into the lateral side of the base of the proximal phalanx of the fifth toe. This tendon usually blends laterally with that of abductor digiti minimi. Flexor digiti minimi brevis flexes the metatarsophalangeal joint of the fifth toe.

Adductor hallucis

Adductor hallucis is divided to oblique and transverse heads. The oblique head originates from the bases of the second, third and fourth metatarsals, and from the fibrous sheath of the tendon of peroneus longus. The transverse head originates from the plantar metatarsophalangeal ligaments of the third, fourth and fifth toes, and from the deep transverse metatarsal ligaments. The medial part of the oblique head merges with the lateral part of flexor hallucis brevis and is attached to the lateral sesamoid bone. The lateral part joins the transverse head and is also attached to the lateral sesamoid bone and directly to the base of the proximal phalanx of the hallux. The transverse part of the muscle attaches to lateral side of the first metatarsal head (Standring, 2016). Total force exerted by transvers branch and oblique branch of the adductor hallucis were measured 3.4 kg and 15.5 kg respectively (Aper et al., 1994). Adductor hallucis partly flexes the proximal phalanx of the hallux, but also stabilizes the metatarsal heads (Oatis, 2009; Standring, 2016). It also provides the counterbalance to the abductor hallucis in supporting the alignment of the first metatarsophalangeal joint (Glasoe, 2016). However, its moment arm is longer than that of abductor hallucis, it creates the deforming forces in hallux valgus.

Lumbricals

The lumbrical muscles originate from the separation angles of the tendons of flexor digitorum longus. However, a recent study of lumbrical muscles anatomy showed that lumbrical muscles originate not only from flexor digitorum longus tendon, but also they originate from flexor hallucis longus and quadratus plantae tendons (Hur et al., 2015). Their tendons pass distally on the medial sides of the four lateral toes and are attached to the dorsal digital expansions on their proximal phalanges (Hur et al., 2015; Standring, 2016). These both ends of the lumbrical muscles mobile; they may produce movement on either end. They provide interphalangeal joint extension while metatarsophalangeal joints move into flexion. They also provide intermuscular and proprioceptive bridge and play a role as a regulator between flexor and extensor muscles (Fig. 23.32) (Wang et al., 2014).

Pathology of the lumbrical muscles may lead serious forefoot deformities such as claw toe and hammer toe deformity, which commonly have been seen in diabetic foot (Cheuy et al., 2013), and buckling of toes under the foot during walking. If such toe deformities occur because of any other reason, metatarsophalangeal joints became hyperextended and intact lumbrical muscles may not produce sufficient flexor moment (Myerson and Shereff, 1989).

Plantar interosseals

Three plantar interosseal muscles lie below the metatarsals and originate from the bases and medial sides of the third, fourth and fifth metatarsals (Fig. 23.33) (Standring, 2016). Earlier study revealed that interosseal muscles were not originated only from bone tissue, but also long plantar ligament, and the plantar metatarsal and tarsometatarsal ligaments (Kalin and Hirsch, 1987). They insert into the medial sides of the bases of the proximal phalanges of the corresponding toes, and into their dorsal digital expansions. The plantar interosseal muscles adduct the third, fourth and fifth toes. Adduct the third, fourth and fifth toes to the axis of the second toe as well as flex the metatarsophalangeal joints and extend the interphalangeal joints (Standring, 2016).

Dorsal interosseals

The dorsal interosseal muscles are lie between the metatarsals. Each of them originates as two heads from the sides of the adjacent metatarsals. Their tendons are attached to the bases of the proximal phalanges and to the dorsal digital expansions similar to lumbrical muscles. The first dorsal interosseal muscle inserts into the medial side of the second toe; the other three insert to the lateral sides of the second, third and fourth proximal phalanges (Fig. 23.33) (Standring, 2016). Primary action of dorsal interosseal muscles are abduction of toes an flex the metatarsophalangeal joints and extend the interphalangeal joints of the lateral four toes (Mann and Inman, 1964). Weak interosseal muscles lead to claw-toe deformities.

Dorsal intrinsic muscles

Extensor digitorum brevis

Extensor digitorum brevis is a dorsal intrinsic muscle that originates from the superolateral surface of the calcaneus, from the talocalcaneal ligament, and from the deep surface of the inferior extensor retinaculum (Fig. 23.33). Ends in four tendons at the dorsum of the foot. The medial part of the muscle is named extensor hallucis brevis, insert into the dorsal aspect of the base of the proximal phalanx of the hallux. The other three tendons attach to the lateral sides of the tendons of extensor digitorum longus for the second, third and fourth toes (Oatis, 2009;

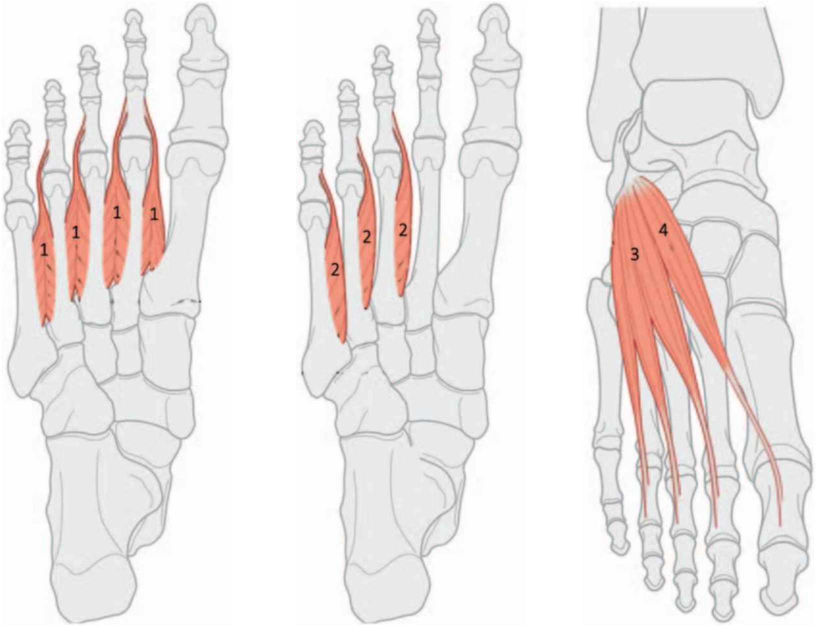

FIGURE 23.33 Dorsal intrinsic and interosseal muscles; 1) Dorsal interosseal muscles, 2) Plantar interosseal muscles, 3) Extensor digitorum brevis. *Reprinted with permission from Elsevier, Drake et al. 2015.*

Munakomi and Kumar, 2016; Standring, 2016). The muscle assists to extensor digitorum longus in extending the phalanges of the middle three toes, medial slip assists in extension of the first metatarsophalangeal joint. Weakness of extensor digitorum brevis leads to slight functional impairment because the extensor digitorum longus can compensate this weakness.

Forces produced by intrinsic and extrinsic foot muscles are transmitted by the plantar fascia and other noncontractile tissues, act across the numerous rear, mid and forefoot joints and are thus assumed to contribute to foot functions particularly in dynamic condition (Angin et al., 2018). Their contribution may not be direct, but they regulate the stiffness of the foot and plantar fascia, which is the major contributor to maintain the foot posture (Kirby, 2017; Angin et al., 2018).

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Part 7

Sensory-motor integration and performance

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Chapter 24

Motor control and sensory-motor integration of human movement

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Physiological basis of motor control

Understanding motor control

Human movement is a complex and interesting series. In fact, the perception of sensory stimuli that is consciously or unconsciously transcribed is also involved in the process of cognitively storing and organizing of motor movements. Any movement occurs with a combination of postural tonus, balance and muscular coordination. Activities such as functional use of upper and lower limbs, fine hand skills, balance, and walking can be performed in daily life. The sensory-motor integration that takes place in this process results in a smooth human movement with motor control. This integration is firmly attached to each other at all levels (Glencross, 1995). Motor control is the ability to regulate or direct the mechanisms necessary for movement. The person adapted their movements for environmental demands and tasks for sensory, perceptual and cognitive skills (Shumway-Cook and Woollacott, 2016a). Many structures, especially the cortex, are involved in the formation of the movement.

Kinesiology is related to movement and structures (Illustrated Stedman's medical dictionary, 1982). Therefore, kinesiology must be well known for the understanding and resolution of any problem (Greene and Roberts, 2005a).

Neuroanatomy and neurophysiology

Motor control is consisted of mixed models, composed of peripheral and central systems. Sheridan (1991) described that both peripheral and central mechanisms play an important role in the organization, motor control and human skills (Sheridan, 1991).

Sensory stimuli are taken up by the respective receptors which are placed on skin, muscles, joints, eyes, ears, and related tissues in the peripheral system. These stimuli are first transported to the center via the nerves, fibers, pathway, etc. Movement is made by the cortex and supported by basal ganglia, cerebellum, etc. The motor organization is controlled by Spinal cord, especially anterior horn. Axial muscles (medial vestibulospinal and reticulospinal tract), proximal and distal limb muscles (lateral vestibulospinal, reticulospinal tracts), and reinforces axial and limb movements (corticospinal tracts) is regulated by Spinal motor organization (Young and Young, 1997a; Shumway-Cook and Woollacott, 2016b).

Sensory-motor feedback and perception of movement

Sensory systems

These systems are composed of somatosensory system, vestibular system, auditory system, and visual system. The somatosensory system starts from receptors and continues to the dorsal column medial lemniscal and the pathways of anterolateral system. Vestibular system, in the same manner, starts from the receptors and transferres to vestibular projections. The interactions between proprioception systems cause postural adjustments and movement. Auditory system is related to ear. Firstly sound waves come from external ear, and then it is transmitted via the middle ear. In the end, it is transduced within the inner ear. Its receptors are called hair cells. Visual system is the same as other systems, takes visual information via photoreseceptors. The information transduction change light into the electrical signals. Then information is transported via the optic nerve to occipital lobe. Producing and planning motor behavior, motor control, are also

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important accurate interpretations of sensation. The somatosensory systems and vestibular systems contribute to development of postural responses, body scheme, postural tone, equilibrium, and also stabilization of eye, and head during movement. Visual system is also play a role in coordination of posture and eye movements to visual, auditory system have also play a role in controlling orientation of head, eyes, and body to sound (Lane, 2002a).

Sensory inputs

All receptor sites, axons and branches of an afferent neuron bring the sensory unit to the center, and the receptive fields of these units are so intricate that the exact boundaries of sensory fields can not be separated. Sensory receptors convert various types of energy from the inside and the outside of the body into depolarization. Each receptor is stimulated by its own energy, but if the neural stimulus is too intense, activation may occur outside of its modalities in some receptors. The magnitude of depolarization depends on the stimulation intensity of the receptor. The stimuli, which are above and below the threshold, allow the stimulus to be transmitted by creating the action potential in the sensory nerve of the receptor (Shumway-Cook and Woollacott, 2016b; Fitzgerald et al., 2012a; Young and Young, 1997b). The senses are transported by nerve fiber types such as A alpha (proprioceptive and motor), A beta (strong touch, pressure and motor), and A gamma (motor to muscle spindles), etc. In this case, lateral inhibition is made on dermis because of presence of inhibitor interneurons. The localization of the stimulus and the ability to distinguish it are made so that a stimulus coming from the dermis does not spread too much while spreading rapidly and strongly. Peripheral nerves carry information to medulla spinalis. Medulla spinalis transmits it to the corresponding laminae of the information about the nerve-related stimulus entering medulla spinalis from the posterior root (Shumway-Cook and Woollacott, 2016b; Young and Young, 1997b; Fitzgerald et al., 2012b). Laminae have important roles in sensory inputs and motor outputs. For instance Lamina V and VI are related to proprioceptive descending/efferents and fibers starting from the motor and sensory cortex. It is thought that they have functions related to regulation of movements. Lamina VII has many connections with the mesencepheleon and the cerebellum. This lamina plays an important role regarding the regulation of posture and movement. Lamina VIII plays a role in regulating the contraction of striated muscles through alpha motor neurons in the lamina IX. Lamina IX cells are motor neurons. Two type cell types are important there: alpha and gamma motor neurons. The larger ones are alpha motor neurons and it's provide the extrafusal fibers of the skeletal muscles. The gamma motor neurons are the smaller and it's provide the intrafusal fibers of the muscle spindles. Gamma motor neurons have spontaneous discharge characteristics. In this case, the muscular normal tone continues because the polar regions of the muscle spindles always have some contraction. However, spontaneous discharges of the gamma motor neurons are kept at a minimum level by the signals coming from the upper centers and spinalizing the medulla by the innate pathways. During movements and postural adjustments, alpha and gamma motor neuron' co-activation lets spindles to function at all muscle length. If there is a problem with this connection, the muscle tone becomes increasingly pathological (Fitzgerald et al., 2012c).

One of the important structures in the spinal cord is the locomotor pattern generators. Locomotor pattern generators are circuits that produce movements in the manner of flexion and extension especially in spinal cord cervical and lumbar regions. Even if peripheral sensory stimuli are not present, the mesencephalic locomotive region is activated by tonic discharges of the region. It is thought that the neurons initiate the movement rhythmically without warning from the upper centers by forming reflex patterns such as walking, running, etc. The central pattern generators receives information from receptors such as visual receptors, proprioceptors, vestibular receptors, etc. (Fitzgerald et al., 2012b; Latash, 2012).

Sensory stimulus is carried by the anterior system and the dorsal column-medial lemniscal (DCML) pathway to cortex. Proprioception, vibration, strong tactile and pressure senses are carried in the dorsal column. Pain, heat, superficial touch, superficial pressure senses are carried in the anterolateral system (Lane, 2002b). Since sensory input is important in autonomic responses, somatic and visceral sensory neurons, brain stem, hypothalamus, and limbic system are involved in the process (Shumway-Cook and Woollacott, 2016b; Lane, 2002b).

Reticular formation has a very important role in the integration of the senses up to muscle tone. Reticular formation consists of median, paramedian, and lateral column. The lateral column, parvocellular column, gets afferents from the sensory components of all cranial, spinal and peripheral nerves. This column plays an important role in sensory integration. Paramedian column is composed of axons to the brain and spinal cord. The median column has seratonergic neurons. Aminergic neurons (seratonergic neurons, epinephrine-secreting neurons etc.), pattern generators (a midbrain locomotor area that regulates walking), antinociception (segmental antinociception, supraspinal antinociception) are actively playing a role in the movements (Fitzgerald et al., 2012b). At the same time, the brainstem system affects our motor movements and forces the cortex to stay awake. The best example of this, is the fact that we start walking to avoid falling asleep and to keep staying awake.

Actually, cerebral cortex is a structure that contains many processes and connections from the perception of sensory stimuli from the periphery to the planarization of motor movement. The most active lobes in the motor control are the parietal and frontal lobes. Other areas of the brain also contribute to the control of movement (Rosenbaum, 2010a). There are three kinds of fibers named as association, commissural and projection fibers, leaving the cerebral cortex (Fitzgerald et al., 2012d) Looking into lobes of the cortex, frontal lobe contains important areas as primer motor, premotor, prefrontal cortex and supplementer motor cortex. The primer motor lobe provides individual or synergetic movements of muscles of an extremity when the motor cortex is stimulated. The premotor cortex is responsible for our learned motor movements for a general function and is responsible for the task of adjusting posture and position for movements. Another important feature of the premotor cortex is that it has mirror neurons in its silent activation. These neurons monitor the movement and release the same movement. Likewise, in mental imaging, activation in mirror neurons under the premotor cortex and parietal cortex is important in learning new motor movements with motor sensing, empathy, and imitation. Supplementer area plays a role in bilateral muscle contractions. The main role is in the distal muscles of the two hands in coordination with each other. The premotor area is responsible for the same task of proximal muscles. Since the fine motor movements are controlled by the pyramidal system, the fibers of this system allow the lateral corticospinal pathway to descend directly into the spinal cord. The number of synapses is small. Prefrontal cortex is related to problem solving, decision making, emotion, and executive functions. There is a close relationship between this region and the limbic system in the presence of our personality and the appearance of appropriate behaviors. Parietal cortex is also related to the sense of discrimination. Brodmann areas of 3-2-1 is especially related to somatosensory senses. Thalamic fibers also come from regions 3a and 3b. Areas 2 and 3a play an important role in proprioception and kinesthesia. Hand-related gripping skills, hand-eye coordination, speech, and visual is related to different Broadman areas in the cortex. For instance; Broadman 22 is a secondar hearing cortex and is related to the localization and direction of the voice. The Reticulospinal tract (lateral lemniscus) plays a role in hearing response. These fibers are responsible for controlling the orientation of the body, head and eyes by moving inferior and superior colliculus. The occipital lobe is related to vision. Brodmann 17 is known as the primer visual cortex, whereas 18–19 are the seconder visual cortex. These areas connect to inferior temporale and posterior parietal lobe (dorsal, ventral stream) and percieve information about objects. Visual inputs play an active role to maintain balance (Lane, 2002b).

These inputs contribute to the formation of movement within a wide visual-motor environment. Especially if we have a ball or object that we control by hand, the concepts such as angles, torques, distance and power in our joints gain more importance here. In our daily life, we manipulate many objects according to their different kinematic and dynamic characteristics. These can be used while driving, using the computer, doing sports. For all of them, we need to use special sensorimotor transformations that are tailored to the specific situation for each of them in different visual environments CNS. The control of limb movements to the target is very important because of the control variables to be determined, because it is much larger than the number of input variables that determine the motor task. If the visuomotor coordinates the conversion, the degrees of freedom of the arm and body may be much greater than the degrees of freedom that determine the visual position of the target. Therefore, the CNS should specify an infinite number of variables for a continuous transient trajectory hike, which is only finalized in the arm arrangement. In the command production for motor motion, the number of joint torques, muscle tension, motor neuron activation, and firing patterns of motor cortical neurons are much greater than those of the angles of angular velocities and acceleration that are sufficient to indicate the arm trajectory (Kawato and Wolpert, 1998).

Coordination in purposeful movement

When planning a motor action, cerebral cortex initiates at least four circuits involving basal ganglia and then these circuits return back to the cortex again. These are: *a motor loop* which is related to learned movements, *a cognitive loop* which is concerned with motor intentions, *a limbic loop* which is related to emotional aspects of movement, and *an oculomotor loop* which is concerned with voluntary saccades. Normally, *motor loop* is related to sensorimotor cortex and returns there via the striatum, thalamus and SMA. The basal ganglia need to be stimulated by the SMA activated by sensory stimuli from the periphery in order to initiate movement on the opposite side of the body. Premotor areas including the cerebellum made action and sent stimulation via corticospinal tracts. *Cognitive loop or prefrontal loop* , participates in motor learning via prefrontal cortex and basal ganglia. Especially, firstly a novel motor action is performed by one hand, basal ganglia, thalamus are also activated. Then the movement of the thalamus, premotor and prefrontal cortex is planned with cortical connections. If the learning takes place by repeating the movement, *the motor loop* is now activated. *Limbic loop* plays a role in giving motor expression to emotions, for example; smiling. This loop connection with thalamus, basal ganglia, prefrontal cortex etc. *Oculomotor loop* begin in the prefontal cortex and parietal cortex. It connects to basal ganglia and thalamus (Fitzgerald et al., 2012e). For example, for a new child to begin basketing, the cognitive loop is activated. As the motion is learned, the motor loop takes over the task. If the ball is to be thrown to the target, eyes are fixed by the oculomotor loop, and if the face will smile, limbic loop organize that action. Many sensory stimuli, such as the size of the ball, the roughness of the surface to which it is touched, are moved through the periphery and the movement is formed by the introduction of many connections including thalamus, basal ganglia, parietal cortex, cerebellum, SMA, premotor cortex.

The basal ganglia is known to be involved in the control of movement (Fitzgerald et al., 2012e). It refers to the large, strongly interconnected nuclear masses deep within the cerebral hemispheres, diencephalon, and midbrain that are instrumental in the initiation of movements and control of the postural adjustments associated with voluntary movements (Young and Young, 1997c). Beside initiating and controling voluntary movements, basal ganglia has addition roles closely related to cognitive aspects of behavior. Therefore basal ganglia receives input from all parts of cerebral cortex, thereby accessing what is going on and programming what needs to be done in the next movements (Young and Young, 1997c). While there is no direct connection between basal ganglia and medulla spinalis, there is a direct connection between cerebellum, brain stem, and medulla spinalis. That is, these differences in the connections indicate that cerebellum is related to the regulation of cortical motor activity, whereas the basal ganglion is related to the perception of complex cortical motor activity and planning (Shumway-Cook and Woollacott, 2016b; Lane, 2002b; Rosenbaum, 2010a). The overall function of this loop is to select a particular movement or sequence of movements, or behaviors, while suppressing others. Contrary to this, cerebellum adds skill to movement for fine tuning.

Cerebellum has an impact on smooth and coordinated movements via timing and adjusting force of voluntary muscles contractions (Young and Young, 1997d). Cerebellum has important role as a perceptual- motor learning (Imamizu et al., 2000), learning to anticipate visual stimuli in reaction time tasks and skillful extremity movements (Rosenbaum, 2010a). Cerebellum receives proprioceptive information from the medulla spinalis for movements. It gets information about audiovisual-vestibular senses from the brain stem. Dorsal-spinocerebellar pathways (proprioceptive sensory incomes - junctions of the joints - following the degree of contraction of the muscles) and ventral spinocerebellar tractors (carrying a copy of the motion command from the cortex to the medulla spinalis) also acquire peripheral information. Although there are many classifications of parts in the cerebellum, as functionally, the cerebrocerebellar section is responsible for planning and coordination of motor movement, the flocculonoduler part is responsible for balance, and the spinocerebellar part is responsible for muscle tone. There is a causative role of the cerebellum when the movement is continued or finished. Consecutive movements are responsible for the speed and coordination of the motor movement. The information is processed in cortex, cerebellum, basal ganglia, and other structures and motor response is generated (Shumway-Cook and Woollacott, 2016b; Lane, 2002b). Then all inputs are sent to the cortex in order to compose motor movement. Especially, the cooperation of these systems is very important in modeling of motor learning. This communication between cerebellum and cortex is also important in motor learning. Because cerebellar fibers in the connection with the cortex of the fibers in the possible motor movement plan in the wrong. Cerebellar fibers are assumed to carry a copy of the feedback motor command generated a crude feedback control circuit. Therefore, Cerebellar feedback error-learning model resolves this difficulty (Kawato and Wolpert, 1998).

The motor movement, composed by primer motor cortex, is carried by ventro- medial system and lateral system to medulla spinalis. The ventromedial system acts as an exciter or inhibitor to muscles. They are responsible for posture and automatic movements. The lateral system is the pyramidal system and has the exciter role only. In particular, the distal flexor is responsible for the movement of the muscles. Medulla spinalis stimulates alpha motor neurons and interneurons of flexor muscles (Shumway-Cook and Woollacott, 2016b; Lane, 2002b) (Fig. 24.1).

Motor control and sensory-motor integration in different life stages

Sensory-motor integration

Sensory Integration is the process of combining sensation between or within a synthesis. It reflects behavior (Lane, 2002a). Jean Ayres defined it as "the neurological process that organizes sensation from one's own body and from the environment and makes it possible to use the body effectively within the environment" (Ayres, 1979). Sensory integration term is consisted of modulation and praxis. Modulation is described as adjustment of circumstances. Neuromodulation is explained as adapting to environmental changes and balancing of inputs, some of them are excitatory others are inhibitory. Modulation is an important issue for motor action (Lane, 2002a).

In reality, four main systems are involved in the sensory-motor integration. These include somatosensory, visual, auditory, and vestibular systems as mentioned before. Lane (2002b).

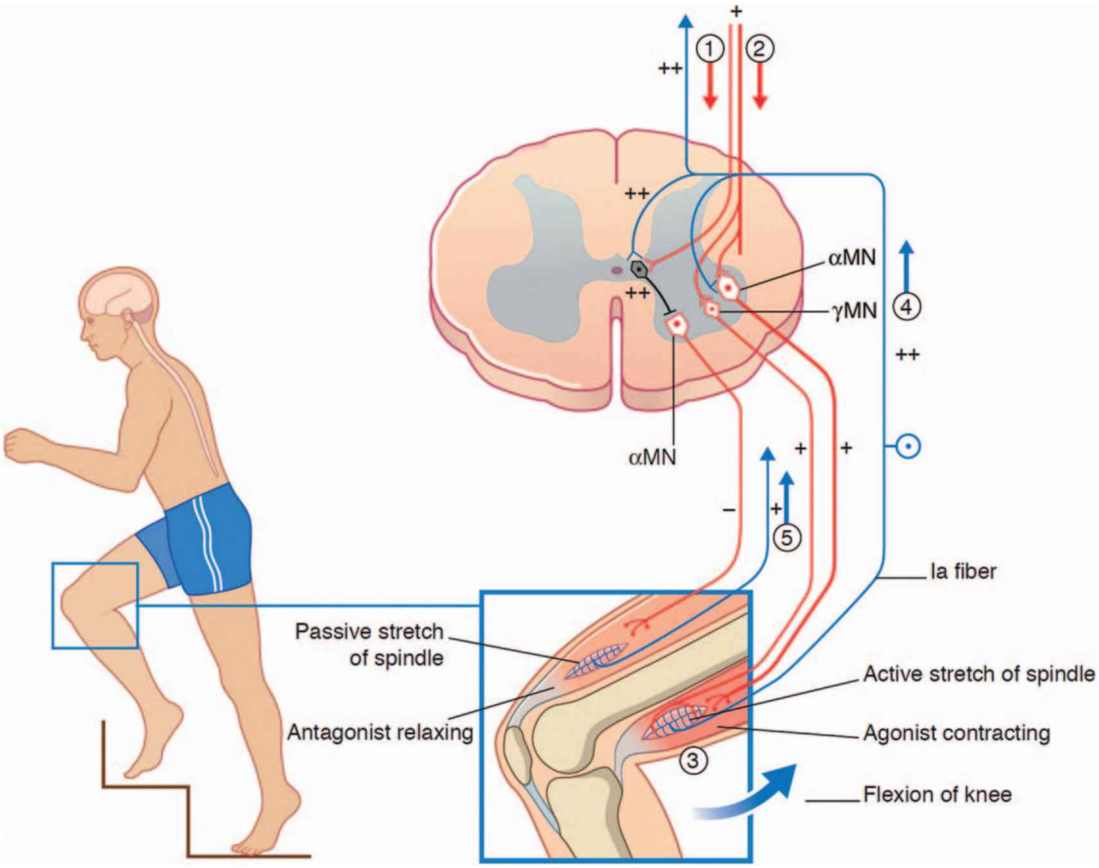

FIGURE 24.1 Sequence of events in a voluntary movement (flexion of the knee). *With permission from Elsevier (Fitzgerald et al., 2012c).*

The motor movement

Motor movement is consisted of ideational, planning, execution of an action, and motivation. Ideational means conceptualizing an action. Planning means plans for motor action. Ideational and planning of motor movement is entitled as praxis. Of course, execution of the action is another part of the movement. Motivation is related to emotion and behavior.

Basal ganglia is partly playing a role in the ideation (Reeves and Cermak, 2001). However, the prefrontal cortex is involved in this process. Goal directed movement and imagine performing are the main roles of the prefrontal cortex. However, areas of planning of movement are significantly lateral premotor and medial supplemotor motor areas (Fuster, 2002). Supplementor motor area is primarily depending on proprioceptive sensory input and it has an active role in bimanual movements, head and eye orientation, and sequential movement. In addition, parietal cortex has an active role in the planning as it is related to proprioception and other sensory systems. On the other hand, it has close connections with motor area (Iyer et al., 1999). Mesencephalon and brainstem, especially locomotor region mentioned before, roles are important voluntary movements of legs (Shumway-Cook and Woollacott, 2016b).

Execution of the movements is provided by motor cortex. Then, this information is sent to muscles via corticospinal and corticobulbar fibers which have synapses in the spinal cord (Shumway-Cook and Woollacott, 2016b; Lane, 2002a).

Motivation has a key role for the control and regulation of the behavior and emotion. The limbic system is involved in the motivation (Iyer et al., 1999).

The limbic system and sensorimotor system are playing a role in the goal-directed movement. Motivations are transformed into ideas via the Limbic system and through cortical processing carried out in the association areas of cortex. Ideas are formed through processes to motor programs. Then it is programmed from the general to the specific and conducted by cortex, basal ganglia, cerebellum, and related subcortical areas. Programmed motor movement is transmitted to the brainstem and medulla spinalis via motor cortex for execution. The planned motor movement is then transmitted back to the upper levels and it is called corollary discharge. Corollary discharge is also composed of the internal loop which is descending motor signals back to the higher centers.

Programmed motor movement is precisely created and transmitted to the muscles by the lower motor neurons via a good muscle coordination. Thus, voluntary movements are made while postural adjustments are made. Feedback can continue to control movements by continuously sending sensory stimuli to the upper centers.

Two mechanisms, called open-loop and closed-loop, are emphasized in neural control of movement. Motor movement is performed in the presence of sensory feedback in the closed- loop. The motion performance is monitored for possible inconsistencies. There is feedback between sensory information and motor movement. This ensures that the motion is reprogrammed properly. Open-loop means motor movement is performed in the absence of sensory feedback. Open-loop, on the other hand, can directly monitor the environment without sensory information (Iyer et al., 1999).

When the movement is learned for the first time, it is achieved slower and more controlled. Over time, the number of repetitions is increased faster and more coordinated. In addition to the control systems, the movement is also automated.

The concepts of human motor control

Identifying specific areas of the human body forms the groundwork for practicing any of the medical art. The central nervous system, the peripheral nervous system, control of movement (bones, joints, muscles, muscle activity, muscle strength, muscle tone) are important to understanding medical concepts of human control. However, only anatomical and physiological aspects are insufficient to understand motor control. Many of the laws of physics are used to understand and explain human movements.

Gravity

Gravity affects every aspects of movement. Gravity imposes itself on our system at every turn-sometimes helping, most of the times hindering. This constant struggle causes us to fall into bed exhausted at the end of the day. Gravity exerts physical effects on bodies to the extent that all internal muscle forces respond in one way or another to the gravity. Voluntary movements are neuromuscular responses to external stimuli or gravity. In early life, gravity acts as both a stimulus and a barrier to movement. Infants must overcome its effects to raise their heads, reach out, crawl and stand. Gravity also stimulates mechanisms (reflexes) within the body and gravity's tug on muscle stretch receptors (muscle spindles) results in muscle contractions. When a baby lies in the prone position with her head unsupported, gravity pulls on the head and produces head and neck flexion that stretches the neck extensors. Likewise, a baby lying in a supine position with his head unsupported experiences gravity pulling the head into extension. Gravity stretches, stimulates and resists the neck flexors. Over time infants gain the strength and experience to control their head movements voluntarily.

Gravity plays a large role in its affect on stretch reflexes, but it also has more subtle effects. For example; the delicate vestibular mechanism of the inner ear, responds to gravity's downward pull on small crystals.

Gravity's force acts on a body's center of gravity by pulling it down toward the center of the Earth. In uniform bodies like balls and cubes, we find the center of gravity located in the exact center of the object. Bodies have three dimensions; therefore we must locate the exact center of three planes, each of which divides the object into equal halves. The body's sagittal plane divides it into left and right halves, its frontal plane separates it into front and back, and its horizontal plane forms top and bottom sections. A person's center of gravity is the point at which the three planes meet.

Our center of gravity changes when we move. The human body moves constantly, so its center of gravity constantly changes. When we stand upright, our center of gravity lies in the abdominal cavity, about 6 in. above the pubic symphysis. As we move our arms and legs, the center of gravity chance.

The extent to which the center of gravity changes and the effect of gravity on our bodies depend on the weight of the body parts (head, trunk, arms, etc.) and their length. We feel the pull of gravitational attraction when we jump. The massive earth causes all objects on it to move toward its center. This pulling force of attraction changes in proportion to an object's mass, but its rate of acceleration remains constant.

A lower center of gravity give more stability to the body. Toddlers begin to walk by bending at the knees and hips, lowering their center of gravity. Stability depends on a wide stance, or base of support, like the one toddlers adopt. The third factor, the projection of center of gravity, exhibits interplay with the base of support.

Balance depends on the projection of center of gravity. When this projection falls outside the base of support, we lose our balance. In our efforts to recovery, we attempt to reposition the projection of center of gravity within the base of support. Weight makes the fourth contributing factor in stability. We know that we have a harder time moving a more massive object. This is the Newton law: force equals mass times acceleration ($F = m*a$).

For example, high-heeled shoes change the center of gravity and shift weight and gravity forward onto the toes. After this forward tendency and maintaining upright balance, the upper back and shoulders shift to move the center of gravity projection posteriorly into a negligible base of support.

Along with aging it is difficult to adapt to changes in the center of gravity. Older adult's gait patterns were similar to those used by someone walking on a slippery surface or someone walking in darkness. The reason of this is the problem of postural control.

Reduced somatosensation associated with peripheral neuropathy is often associated with the aging process, especially in older adults with diabetes. Peripheral nerve dysfunction in older adults was associated with slowing in both usual and fast-paced walking speeds (Resnick et al., 2000).

These fifth factor in stability comes into play each time someone transfers from a wheelchair to a bed, toilet, chair or any other surface. If a person is going to help the patient stand up, the patient should come forward to the edge of the chair and lean forward; shifting center of gravity forward to provide a mechanical advantage in terms of lumbar health of people who helped.

Linear force

We cannot see forces around us, but we feel their effects as deeply as we sense our own breathing.

External forces affect the body from the outside, Newton explained the effects of forces on objects in his three laws of motion as it is explained in the Chapter 2.

Anatomical structures alter their shapes in response to these forces. Compressive forces push tissues together, causing anatomical structures to become shorter and wider. Tention forces pull tissues apart, causing anatomical structures to become longer and narrower. Anatomical structures usually return to their original shapes once the forces acting on them stop.

Elasticity describes a structure's ability to return to its original shape. Injury happens when normal forces exceed a tissue's elasticity.

External forces also can operate parallel to a surface. Raising your arm over your head causes the weight of the humerus to produce a shear force on the glenoid fossa. When stress within human tissue exceeds the tissue's elasticity, tissue breaks down, causing injury.

Internal forces are body tissues. Muscle contractions generate linear forces. In all muscle contraction types (concentric, isometric, eccentric), force vector goes to origin from insertion. Muscle force occurred at the "just-right" length. The resting length of muscle fibers determines excursion, the distance a muscle can shorten. Consider muscle fiber length, not overall muscle length, to determine muscle excursion. Multijoint muscles produce movement at more than one joint.

In a study, comparing patterns of muscle activity in younger and older woman, average EMG activity levels of gastrocnemius, tibialis anterior, biceps femoris, rectus femoris and peroneus longus were higher in the older than in the younger age group (Manchester et al., 1989; Finley, 1969). Older adults show later onset of contraction and smaller magnitudes in the postural muscles activated in balance recovery as compared with the younger adults.

Rotatory force

Rotatory motion differs from linear motion because rotatory motion occurs in a circular pattern. Rotatory motion of a skeletal segment occurs when the force of a muscle contraction is applied to one segment attached to another segment via a joint. Musculoskeletal segments move only in circular paths, but combinations of rotary movements at different joints take us from place to another on linear paths. In rotatory motion, both the force and the point of action of the force on the object are important. Opening and closing a door requires a certain amount of force.

Torque

Torque describes the effectiveness of a force to cause rotation. Torque means tendency to rotate and depends on the amount of force applied and the distance between the force and its pivot, or axis, the center of rotation. Torque equals force times movement arm ($T = F*MA$).

Internal and external torques operate on the human body. Forces operating outside the body produce external torque. Muscles acting on their attachments to bony segments produce internal torque when internal forces of muscle contraction and external forces of the loads. Therefore, we lift create tendencies to rotate in opposite directions of each other at the same joint (Hall, 2002; Luttgens and Hamilton, 2011; Nordin and Frankel, 2001; Greene and Roberts, 2005b).

Examples of moving on

During motor learning, the neuronal loop between the sensory pathways from the periphery, the cerebral motor and the sensory cortices and the cerebellum becomes stronger as the repetitions increase and the neuronal pathway develops.

After learning occurs, in very rapid activities such as playing piano, typing, running, etc., without guessing the peripherally proprioceptive senses, only the stimulus from the sensory and motor cortex predicts the next movement and sends the stimuli to the primary and premotor cortex. Lateral hemispheres stimulate the motor cortex of the brain by bypassing peripheral sensorial informations, allowing the activity to be done very quickly (Rosenbaum, 2010b) (Fig. 24.2).

Disabilities of sensory-motor integration and pathological conditions

Parkinson disease (PD), also known basal ganglia disease, is associated with degeneration of dopamine neurons also called paralyses agitans. Substantia nigra compact is a result of reduced doping of the dopaminergic neurons in the vicinity of the dead transmitter dopant. Symptoms such as rest tremor, akinesia, bradykinesia, hypokinesia (mask face), rigidity, flexion posture, walking with small steps, and balance problems are the most important characteristics. Rhythmical movements are made in the thumbs and fingers as pill rolling at the rate of three to six per seconds. Walking is characteristically stooped over, with shuffling feet, without arm swing, and on gaining momentum, the patient is unable to stop and falls if not gets help. In course of time, handwriting becomes small, speech reduces as whispers. As mentioned before in the limbic loop, it has rich in dopaminergic nerve endings. When it effects, mask face become. Tremor is related to motor loop and spinal cord. Rigitidity is associated somatic musculature especially flexors in PD. The basal ganglia are associated with the brainstem locomotor center. In PD, it causes the reticulospinal tractus to be

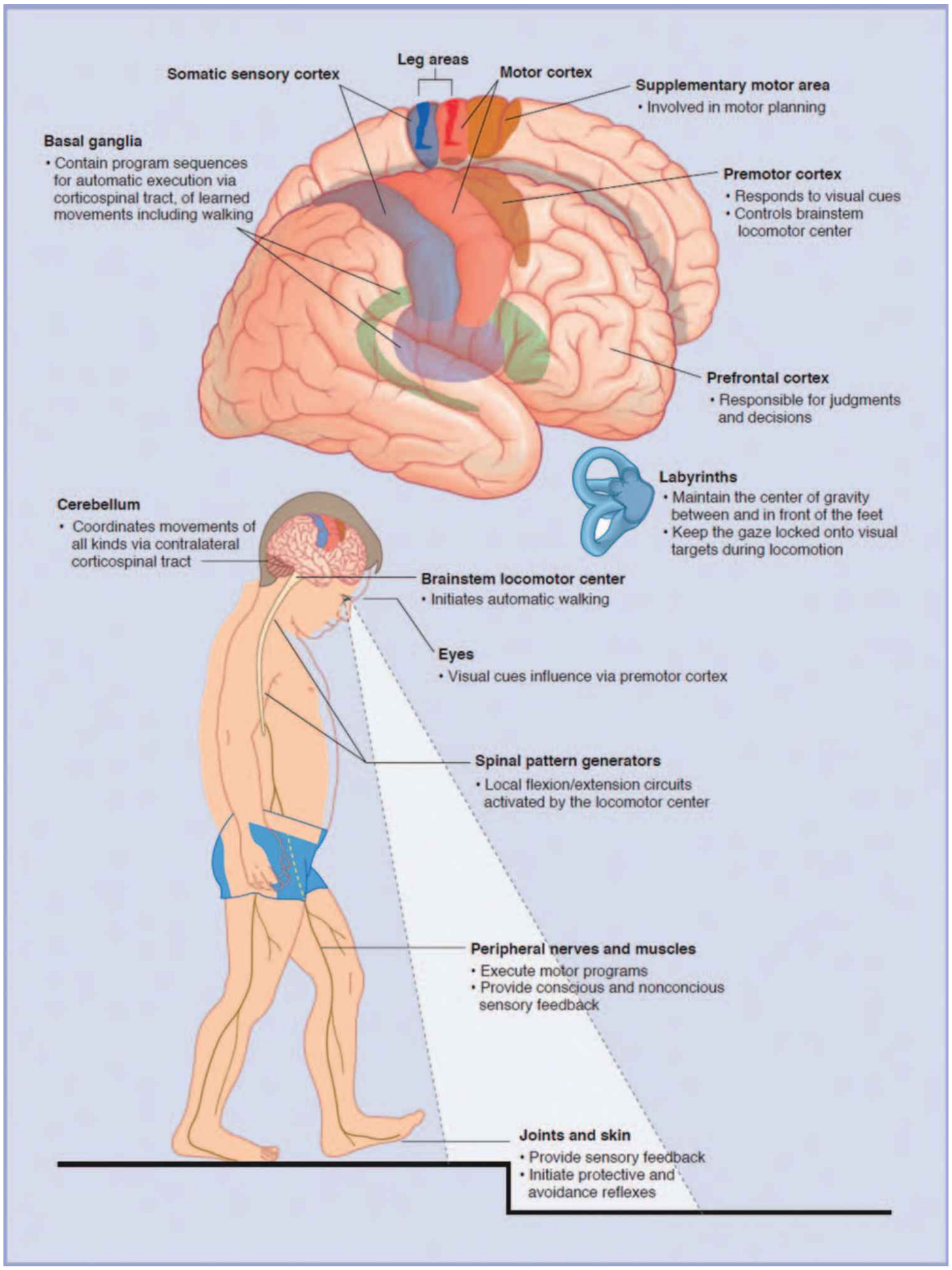
Somatic sensory cortex
Leg areas
Motor cortex
Supplementary motor area
• Involved in motor planning
Basal ganglia
• Contain program sequences for automatic execution via corticospinal tract, of learned movements including walking
Premotor cortex
• Responds to visual cues
• Controls brainstem locomotor center
Prefrontal cortex
• Responsible for judgments and decisions
Labyrinths
• Maintain the center of gravity between and in front of the feet
• Keep the gaze locked onto visual targets during locomotion
Cerebellum
• Coordinates movements of all kinds via contralateral corticospinal tract
Brainstem locomotor center
• Initiates automatic walking
Eyes
• Visual cues influence via premotor cortex
Spinal pattern generators
• Local flexion/extension circuits activated by the locomotor center
Peripheral nerves and muscles
• Execute motor programs
• Provide conscious and nonconcious sensory feedback
Joints and skin
• Provide sensory feedback
• Initiate protective and avoidance reflexes

FIGURE 24.2 Overview of gait (Fitzgerald et al., 2012f). When overviewing gait control, firstly sensory organs as eyes capture visual cues influence via premotor cortex, peripheral nerves provide conscious and nonconscious sensory feedback, and peripheral joints and skin provide sensory feedback and initiate protective and avoidance reflexes. Labyrinths maintain the center of gravity between and in front of the feet and keep the gaze locked onto visual targets during locomotion. Somatic sensory cortex has the important role of motor action as supplementar motor area involve in motor planning, premotor cortex responds to visual cues and controls brainstem locomotor center. Prefrontal cortex is also responsible for judgements and decisions of motor actions. Basal ganglia contain motor program sequences for automatic execution via corticospinal tract, of learned movements including walking. Cerebellum coordinates movements of all kinds via contralateral corticospinal tract. Brainstem locomotor center initiates automatic walking. Spinal pattern generators control local flexion/extension circuits activated by the locomotor center. Peripheral nerves and muscles execute motor programs (Fig. 24.2) (Fitzgerald et al., 2012f). *Thanks to assistance Professor Tim O'Brien to give us permission for using that figure and information from Elsevier.*

adversely affected by this relationship. Impaired reticulospinal activity is showed effected movements of the lower limbs. Difficulties writing is caused of reduction of supraspinal activation.

The basal ganglia participate to movement in milliseconds when the premotor cortex and cerebellum are elevated to the threshold level of the spinal lower motor neuron at the rate of firing of the neurons of the motor cortex. It is known to stimulate the primary motor cortex and oscillator by SMA. In PD, contribution of SMA is weakened and this affects especially the hand and forearm movements and bradykinesia, etc. (Fitzgerald et al., 2012e). Influence of the basal ganglia affects *the loops* mentioned previously and causes such effects as Parkinson's and Huntington's diseases.

Dyskinesia means impairment of voluntary movements and is composed of chorea, athetosis, ballismus, etc. **Chorea** is seen in the striate lesion and it is characteristically consisted of rapid and jerky movements in the distal areas. Huntington chorea is a genetic disease that occurs in adulthood. Sudden and sharp involuntary movements in large amplitude affect head and neck rather than distal parts of the lower and upper extremities. In some cases it may be accompanied by athetosis. In this case it is called choreatetoz. **Athetosis** movements are slow or snake-like movements of the extremites. Chorea athetosis is made of damaged of striatum in the basal ganglia. **Ballismus** is violent flinging movements in the entire extremities as a result of contractions of the more proximal muscles (Young and Young, 1997c). **Hemiballismus** is huge, sudden involuntary movements involving half of the body. Involuntary movements are very violent and anime. While these movements are generally seen in limbs, sometimes neck and facial muscles can also be involved. The thalamocortical pathway became intensely overactive (Fitzgerald et al., 2012e)

Distonnia occurs as a result of a lesion in Nucleus lentiformis (putamen and globus pallisudus) and it may effect movement of posture (Young and Young, 1997c).

Ataxia is commonly seen as a result of cerebrovascular accidents, trauma, tumors or degenerative diseases. It is caused by loss of voluntary movements and coordination Real muscular incoordination affects voluntar movements such as walking, grasping, etc. More common types of ataxia are sensory, vestibullar, cerebellar, and mixed ataxia. Patients with sensory ataxia perform movements in a slow manner and try to compensate for the imbalance by using more of the visual system. That is why, the most significant symptoms can be seen when the patient walks. Patients with vestibullar ataxia may have symptoms such as vertigo and nystagmus, which are accompanied by trunk ataxia. The cerebellum plays an important role in the regulation and monitoring of motor movement by altering the neuronal activity. This causes serious problems in damage. That patients not to produce smooth and well-coordinated movements such as cerebellar ataxia. Especially during movements, they can not to do correcting errors in movement. Cerebellar ataxia, is caused due to affected cerebellum and related connections. This epilepsy is characterized by hypotonia, dysmetria, tremor, discoccal dyskinesia, dyssynergia (impaired elongation of agonist-antagonist and synergist muscles, hand-eye coordination is affected), dysarthria and nystagmus. Kyphosis, lordosis, and scoliosis are commonly seen. The walk is carried out on a large base of support. Step lengths and other stages of gait are not equal due to dissinergy and dysmetria. Mixed type ataxia is the onset of two or more of the above mentioned ataxia (Young and Young, 1997d).

Cerebrovascular disease, a stroke, described as a vascular disorder originated of neurological deficit and its symptoms vary according to the affected area and its size. Hemiplegia is frequently seen after stroke. Motor, sensory or another skills are effected after cerebrovascular diseases (Fitzgerald et al., 2012g).

Multiple sclerosis is a primary demyelinating disease and involves symptoms such as weakness, clumsiness, numbness, and diplopia, which can be correlated with the locations of plaque. Development of multiple disabilities are related to motor, cognitive and sensory problems related to plaques' area in the brain. Motor problems seen as weakness cause of a lesion in the corticospinal tractus. Coordination problems seen as clumsiness cause of a lesion in the cerebellum (Fitzgerald et al., 2012h).

Cerebral Palsy (CP) is caused due to a damage to the brain in pre or natal period. It has different types as spastic, athetotis, and dyskinetic types according to the affected area (Fitzgerald et al., 2012e). It has also some definitions according to the affected extremities as hemiplegia, diplegia, etc. Children with CP also develop movement disorders especially delayed motor movements (Cimolin et al., 2007). Athetosis is generally seen in children with cerebral palsy. Movement is slower, in smaller amplitude, and serpentine involuntary movements than chorea. Some of these children are referred to as choreoathetosis because of the presence of choreiform movements and atelectasis.

Developmental coordination disorders (DCD) consist of delays of motor skills as well as impaired sensory integration (Hogan et al., 2000). DCD is commonly associated with attention deficit/hyperactivity disorder (ADHD), and learning disabilities. They have poor motor skills especially bilateral motor coordination, poor movement control, and motor sequencing deficits (Piek et al., 2012). Motor problems may occur in 30–50% of children with ADHD. Especially bilateral motor coordination and fine motor skills (Jeoung, 2018; Goulardins et al., 2017) effects of premotor area.

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Chapter 25

Motor learning

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Introduction

Learning is a process that refers to changes in behavior and in the central nervous system. Motor learning is defined as: 'a change in the capability of a person to perform a skill that must be inferred from a relatively permanent improvement in performance as a result of practice or experience' (Magill and Anderson, 2007). Motor learning covers three main types of learning procedure; 1) acquisition of a novel motor skill (novel task learning), 2) enhancement of performance of a learned or highly experienced motor skill (expertise), and 3) reacquisition of skills that are difficult to perform or cannot be performed because of injury, disorder or disease (rehabilitation). In order to understand motor learning, it is important to clarify the interrelated terms of motor skill and motor performance. Motor skill refers to a goal-directed activity or task that requires voluntary control over movements of the joints and body segments, whereas motor performance refers to the execution of a skill at a specific time and in a specific situation. Motor performance is an observable behavior, whereas motor learning cannot be observed directly, but rather, can be inferred from performance. Fig. 25.1A and B show the performance of rock climbing skill by professional athletes. Learning of this sport skill starts with observing and imitating an experienced climber. The novice climber closely monitors an experienced climber while experienced climber is ascending. In doing so, the novice might plan some explicit strategies such as, the rock edges for gripping with hands and feet. When attempting climbing, the novice must rely on sensory feedback from proprioceptive and tactile, vestibular, and visual organs for maintaining balance and movement control. In addition, trainers usually give explicit guidance, such as the direction of the next handling, or where to step. Despite all the explicit knowledge gathered by the novice, the practice relies on implicit musculoskeletal and neural processes. As in this example, motor learning and other sensory-perceptual and cognitive learning types often interact to achieve a skilled performance.

Learning hypotheses

Schmidt's schema theory of discrete motor skill learning was originally presented in 1974 at a meeting of the North American Society for Psychology of Sport and Physical Activity (Schmidt, 1975). According to the model, there is a generalized motor program, a schema, for a group of motor tasks. During learning of a motor skill, there are four important parameters to store in working memory. These are; 1) the conditions at the beginning of the movement, i.e. proprioceptive information about the posture, weight of a tool or object that is used, 2) the specifications for the motor program such as, speed and force, 3) the knowledge of results, or actual outcome, and 4) the sensory consequences of the movement response, how the movement felt, looked and sounded. These parameters compose the motor response schema. Important point is that the schema is modified in every execution of the movement based on the sensory feedback and knowledge of results. Schema model involves learning a recognition schema that is an error detection mechanism, and learning a recall schema that is the selection of accurate motor program.

Ecological theory of motor learning has been proposed recently by Newell (Newell, 1991). This model relies on perception-action coupling, and defines that optimal movement strategies are developed in the most efficient way given certain environmental constraints. Perception is important because the person needs to understand the goal of the task, learn the movement and interpret the feedback, both during and after the movement. In this approach, the model highlights the structural and functional constraints related to the individual, task, and environment, and views motor skill as a dynamic exploratory activity in perceptual-motor workspace.

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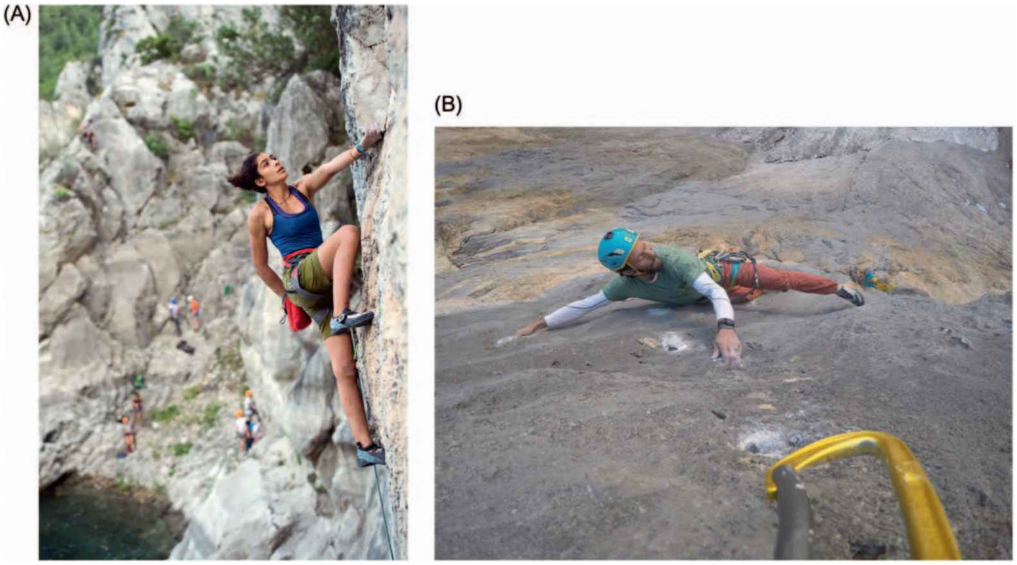

FIGURE 25.1 Rock climbing is an exciting and challenging sport. During learning of rock climbing, beginners practice handling and stepping techniques, which exert pushing, pulling and compression forces to transfer body's center of gravity. Beginners start with low grade top rope climbing or bouldering routes that are easy therefore, more convenient for practising. In photos of rock climbing, performance of two Turkish National sport climbing athletes Duru Güneş Yalçın in 'Kısa Samsun' route (Grade 6c +) (A) and Zorbey Aktuyun during a lead climbing in 'Nessuono' route (Grade 8a + , 27 hours climbing) (B) are shown. Nessuono is a much more difficult route because of the structure of the rock that can be handled only by pinch gripping beyond endurance for 27 hours of climbing (B). Performance at the expert level has an endurance of finer movements and coordinative structure in handling and stepping techniques that are acquired as a result of extensive practice.

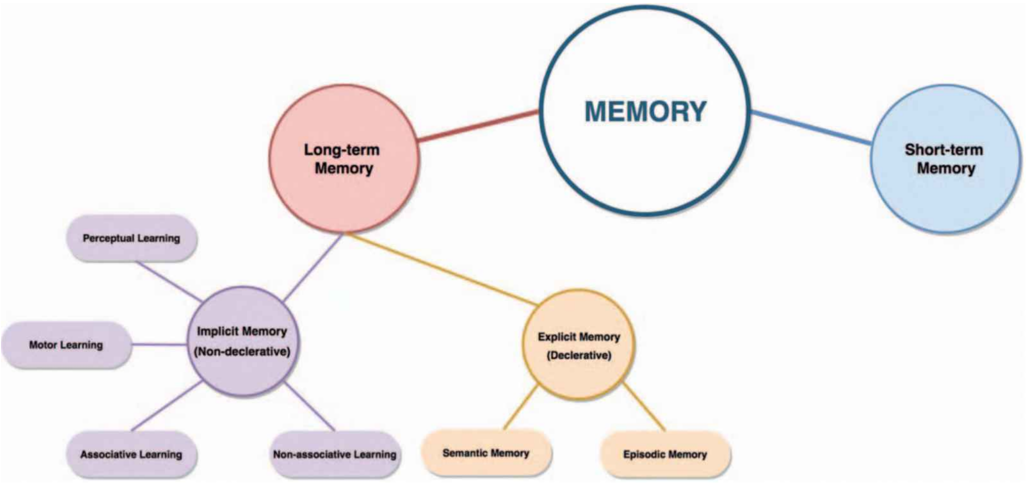

FIGURE 25.2 Classification of long-term memory and different systems of learning are presented. There is an interaction between learning and memory processes. Systems are not fully independent from each other, rather they depend on each other to some extent.

Behavioral approach

Learning and memory are both theoretical constructs, which are interconnected and inferred from behavior (performance). Learning is defined as 'an enduring change in the neural mechanisms of behavior that result from experience with environmental events' (Domjan and Burkhard, 1982). We can divide learning processes into two major types; implicit and explicit. Implicit learning defines an unconscious, yet extremely important process of learning that cannot be described verbally, unlike explicit learning, defined as the conscious process of learning facts, information, and events (Byrne, 1997). Regarding the wider theoretical framework of human learning, 'motor learning' is largely considered as an implicit learning process, and is used interchangeably with the term 'procedural learning'. Fig. 25.2 shows different types of learning and memory, and the place of 'motor learning' in this framework.

Below is the description of different learning types.

Perceptual learning

This refers learning perceptual skills, such as differentiating two colors, or the identification of different food tastes. Examples can be expanded for other sensory modalities; auditory, tactile, olfactory, and proprioception. Perceptual learning can be viewed as an essential part of complex cognitive functions. For example, being able to discriminate close sounds is a clear advantage in language learning (Ward, 2015). Similarly for motor learning, extracting and discriminating relevant sensory information is essential (Wolpert and Flanagan, 2010). Experienced soccer players showed advanced visual discrimination of an opponent's postural orientation, which enables them to anticipate their next movement (Williams, 2009), and to find relevant sensory information more quickly (van Maarseveen et al., 2015).

Associative learning

Associative learning modifies the behavior via relating one stimulus with another, or relating a stimulus with a particular behavior. In classical conditioning, a person pairs two stimuli, and therefore reflex response is modified. In operant conditioning, a person pairs his/her own behavior with the consequences of that behavior (Kandel et al., 2000). *Classical conditioning* is a simple form of associative learning, where the behavioral response is modified by conditioned stimulus. In the classical example, developed by Ivan Pavlov, dogs produce reflex response of salivation when conditioned with a sound stimulus. In the experiment, dogs associated the sound stimulus with the food (natural stimulus leading to salivation response) after sufficient conditioning. Then, the dog shows salivation response to the sound in the absence of food. Classical conditioning is usually related to 1) emotional responses and 2) skeletal muscle responses. Eye blink conditioning is a form of classical conditioning that has been studied in the investigation of neural mechanisms underlying learning and memory. A mild air puff is a natural stimulus that results in an eye blink reflex. In the experiment, the air puff is paired with visual or auditory stimuli, so that, for example, eye blink reflex is seen when a person hears a sound. The eye blink conditioning experiments showed the important role of cerebellum in associative learning; especially in acquisition and timing of motor actions (Gerwig et al., 2007).

Operant conditioning (also called trial-and-error learning) is another type of associative learning in which a voluntary motor behavior is strengthened or weakened, depending on its favorable or unfavorable consequences. When motor behavior is associated with desirable consequences such as a reward (positive reinforcement), there is a tendency to repeat the behavior. In the opposite situation, when the behavior results in unwanted consequences, such as pain or failure (negative reinforcement), it will decrease the likelihood of its occurrence. In rehabilitation science, operant conditioning of spinal reflex has been investigated as a promising tool for locomotion. Simply stated, stimulus-induced muscle responses (reflexes) are used to induce neuroplasticity. In a study by Wolpaw's group, patients with incomplete spinal cord injury decreased H-reflex of soleus muscle with operant down-conditioning, which was associated with faster and more symmetrical locomotion (Thompson et al., 2013). Similarly, operant up-conditioning has been led to increase in motor-evoked potential of tibialis anterior in incomplete spinal cord injury (Thompson et al., 2018).

Nonassociative learning

Nonassociative learning involves learning the properties of a single stimulus. Simple forms of *non-associative learning* consists of habituation and sensitization. Habituation refers to diminishing response amplitude, while sensitization refers to increasing response amplitude to the repeated stimulus (Kandel et al., 2000). Habituation is important for minimizing the energy expenditure of the motor system. Studies have shown that large automatic responses to unexpected movements of a supporting platform are progressively decreased due to a generalized habituation in the postural control system (Keshner et al., 1987). Similar postural control responses occur very frequently in everyday life, for example, while standing in a moving bus, sudden braking results in larger postural reactions at first, but subsequent similar braking results in less dramatic postural reactions. In addition, habituation may be an important factor to consider in orthopedic injuries. Stretch reflex response of the lateral ligament and peroneal muscles are considered to have a role in prevention of ankle sprains. It has been shown that after ten consecutive trials of ankle inversion (as if there is a lateral ankle spraining force), stretch reflex response amplitude decreased 20–50%, suggesting increased risk for injuries (Jackson et al., 2009).

Cognitive approaches

A major part of human learning consists of interplay between cognitive functions, such as thoughts, memories and expectations. Here, we consider observational learning and learning through imitation. The concept of *observational learning* was introduced by Albert Bandura. He demonstrated that children imitated the violent behaviors of adult models towards a toy (Bandura et al., 1963). This type of learning is very important for learning clinical procedural skills, such as injection, intubation etc. Imitation of a model is strengthened if the model is rewarded for that particular behavior. In humans, observational learning is associated with mirror neurons, a group of neurons in the supplementary motor area and in the medial temporal lobe, which show response during both execution and observation of actions (Rizzolatti et al., 1996; Mukamel et al., 2010). Mirror neurons have been found to show response to specific type of goal-directed movements in upper extremity functions, such as grasping and facial emotional gestures. Therefore, it has been suggested that mirror neurons are important for interacting with objects, and also for social cognition particularly for understanding the actions of others (Heyes, 2010).

Memory

Memory is created through learning. It is defined as ‘a theoretical term used to determine instances in which subjects’ current behavior is determined by some aspects of his previous experience’ (Domjan and Burkhard, 1982). Remembering threatening situations or locations where food has previously been found has an evolutionary importance. It is also meaningful for the energy system; if a motor behavior is repeated very often, it should be stored so when needed again, the neural and musculoskeletal systems consume less energy. Adaptation to repeated actions results in change in nervous and musculoskeletal systems. This ability to change is called plasticity. Neuroplasticity describes the change in synaptic properties of neurons in response to environmental stimulation, and in recovery from brain and spinal cord injuries (Merzenich, 2013). Neuroplasticity is greatest during childhood, when synaptic connections bloom and are pruned, but it has been known to persist through the life span, although to a lesser extent. A similar tendency of plasticity exists for skeletal muscles, which have great adaptive and regenerative capacity in response to environmental mechanical stimuli, exercise and injury throughout the life span, but particularly during early periods of development (Mersmann et al., 2014).

Memory may have several components, including visual, phonological or olfactorial. For example, memories of your mother may be triggered by hearing her name, smelling her perfume, seeing her photo, and hearing her voice. The memory can be divided into two categories; short-term and long-term memory (Fig. 25.2). Long-term memory may be further subdivided into different components in relation to how learning is acquired. This model is termed the multiple memory systems approach (Nyberg, 1996).

Short-term memory holds information for 15–25 s, and has a limited capacity (Feldman and Garrison, 1993). For example, you can hold a phone number in your short-term memory while dialing, but once dialed, it is forgotten. *Working memory* is a short-term memory buffer with a limited capacity. It describes the work-bench of the mind, where we hold the significant information active for ongoing mental process of comprehension, solving problems, and decision-making. Therefore, working memory is an important capacity during motor skill acquisition. Indeed, a stronger visuospatial working memory is associated with faster learning of manual skills in the early phase of practice (Anguera et al., 2010, 2011; Ruitenberg, De Dios et al., 2018). This association has been related to individual differences in explicit strategies used to achieve the manual task (Christou et al., 2016).

Long-term memory stores information on a relatively permanent basis, and is considered to have unlimited capacity within the inherent compounds of the brain. The declarative long-term memories can be consciously accessed and declared and has two distinct types; semantic memory and episodic memory (Fig. 25.2). An example for semantic memory is remembering the names of all objects associated with the color red. This gives us a semantic word tree, which is important in language learning. The second clearly defined type is episodic memory. This covers episodes, events in a person’s life and conceptual issues such as subjective time and consciousness (Tulving, 2002). A type which cannot be declared is *procedural memory*, referring to *motor memory* for skills like cycling. This is a type of long-term memory; e.g. we never forget how to ride a bike, swim or play tennis.

Four different stages in memory formation can be defined: encoding and storing newly acquired information (encoding), transferring encoded information from an unstable state to a more stable state (consolidation), retrieving the information when needed (retrieval), and updating the information and re-storing it (reconsolidation). An important stage is consolidation, which stabilizes information in our memory. Motor memory significantly differs from declarative memory in consolidation phase. In every trial of the task motor memory has ‘savings’, a term used to describe a more rapid rate of relearning compared with the original learning (Krakauer and Shadmehr, 2006). If you have previously practiced a novel motor task, the next time you memorize the movement pattern, meaning that you relearn it faster because of ‘saving’ in the motor memory. Savings of motor learning have been observed after one day (Bédard and Sanes, 2011; Villalta et al., 2013; Seidler et al., 2016), one month (Della-Maggiore and McIntosh, 2005), five months (Shadmehr and Brashers-Krug, 1997), and even as much as one year after initial learning (Landi et al., 2011).

Savings can be better understood with online and offline processes during motor learning and formation of motor memory. Online process describes the gain or loss in motor performance during a practice session, and offline process refers to performance changes occuring between subsequent practice sessions (Dayan and Cohen, 2011).

Offline learning is related to neuroplasticity (Muellbacher et al., 2002), thereby the type of activity after the practice session might interact with the offline learning process. While sleep enhances offline learning (positive transfer) (Walker et al., 2003), performing interfering motor task has been shown to abolish motor memory consolidation (negative transfer) (Brashers-Krug et al., 1996).

Physiological approach

Motor learning or training induces structural and functional changes at neuronal level. These changes include increase in the number of neurons, reorganization or expansion of cortical motor and sensory maps, modulation of neuron's firing rate and synaptic transmission. These findings were shown in animal and human studies. Learning new acrobatic movements, rats showed increased number of synapses per Purkinje cell in cerebellum (Black et al., 1990). Also in motor cortex, rats trained on a skilled reaching task showed enlarged cortical representations of wrist and digit movements, and more synapses per neuron (Kleim et al., 2002). Functional reorganization of the human brain is shown in a study using TMS, which showed piano practicing expanded the cortical representation of finger movements (Pascual-Leone et al., 1995). Likewise, increased sensory-perceptual skills, for example auditory discrimination, is associated with the expansion primary sensory cortex (Recanzone et al., 1992; Recanzone et al., 1993), and sharpening neural tuning (Schoups et al., 2001). In another study about piano practice, increased white matter fiber tracts were shown (Bengtsson et al., 2005). The structure of white matter fiber tracts regulate the timing and speed of action potentials across axons. Neurons change their synaptic properties in response to transmission of action potentials. According to Hebb's learning rule, "neurons that fire together, wire together" (Hebb, 1949). Therefore, training-induced plasticity in the primary motor cortex may occur through lasting modulations in synaptic transmission, including synaptogenesis and the coordinated strengthening, e.g. long-term potentiation, and weakening, e.g. long-term depression, of synaptic connections.

Acquisition and retention of motor skill leads to structural and functional changes at cortical and subcortical levels in the central nervous system. These changes evolve over time and engage different brain regions. Functional magnetic resonance imaging (fMRI) studies suggested that prefrontal, parietal and partly hippocampal brain regions, in addition to sensorimotor cortical-striato-cerebellar networks, are active during the initial stage of motor learning (Kami et al., 1995; Honda et al., 1998; Floyer-Lea and Matthews, 2005; Albouy et al., 2008). The premotor area seems to play an important role to initiate new programs for movement and introduce changes in programs that are in progress. In later stages when the attention demand decreases, there is lower level of prefrontal activation (Poldrack et al., 2005).

The serial reaction time (SRT) task is a widely used motor paradigm used to study neural correlates of motor learning. In the SRT task, a stimulus appears on a computer screen, and the participant is instructed to press the specific key assigned to that stimulus as quick as possible. The order of stimuli follows a predictable order, but the participant does not initially know this. During the task, reaction time decreases as a result of motor learning. If the order of stimulus is changed, then the reaction time increases. In SRT, some individuals can verbally express the order of the stimulus, but even for those who cannot reaction time still decreases (Willingham et al., 2002). Neuroimaging studies make use of this paradigm to differentiate neural networks involved in implicit and explicit learning. The neural distinction between implicit and explicit learning comes from a case study, H.M. Surgical removal of bilateral medial temporal lobes resulted in loss of explicit, but not implicit learning (Corkin, 2002). In most cases of motor skill acquisition, both implicit and explicit components are present; an fMRI study neatly showed that basal ganglia is related to the implicit component of learning, and, the prefrontal cortex to the explicit component (Destrebecqz et al., 2005). These findings show the neural correlates of online motor learning. A newly acquired motor skill is transferred from an unstable to a more stable state during consolidation phase, or, in other words, during offline motor learning. Primary motor cortex (M1) has been found to be essential to early stage of motor consolidation. It has been shown that acceleration and muscle force generation of newly learned finger movements have been disrupted when M1 is stimulated by repetitive transcranial magnetic stimulation (rTMS) (Muellbacher et al., 2002).

Neural networks activated during motor learning are different from those activated during adaptation. During motor learning of, for example, typewriting, activation occurs in a large neural network of sensory and motor cortices in the frontal and parietal lobes, basal ganglia and cerebellum. In motor learning, initially whole network is active but later activity in cerebellum, but not the basal ganglia, decreases. In motor adaptation, however, the cortico-cerebellar network continues to be active, while the activity in the basal ganglia decreases (Forssberg, 2008). The role of cerebellum during motor adaptation is very prominent, since it was found to be important for predicting the state of the body during movement (Miall et al., 2007). The cerebellum estimates the sensory consequences of movement, and the response of the cerebellar neurons has been shown during motor learning of head movements. The difference between motor command and motor output led to robust response of cerebellar neurons, demonstrating sensitivity of neurons to cerebellar predictions (Brooks et al., 2015). Further knowledge about the neural correlates of sensory motor adaptation is given in Chapter 27, The effects of weightlessness on human body: spatial orientation, sensory-integration and sensory-compensation.

Motor adaptation

Motor skill performance is dependent on the person, performance environment and the skill level interaction. Context differs every time we perform the task. Performance may be influenced by level of stress, emotional state, environmental factors, such as the ground, change in temperature, and even wind speed. Motor adaptation, usually termed sensorimotor adaptation, is the ability to adjust behavior to changing environmental or internal demands to execute appropriate, goal-directed motor performance. Briefly, the difference between motor learning and motor adaptation is that in the former a new motor program is learned and, in the latter, a pre-existing motor program is adapted. Because of adaptation, movement may change in pattern of force or direction. It requires the modification of the movement based on error signal (Martin et al., 1996). The error signal is the difference between the brain's predicted outcome of the movement and the observed movement; the nervous system needs to reorganize itself to reduce this signal (Tseng et al., 2007). Once adapted to the new condition, individuals cannot easily readapt their prior behavior; instead, they must 'de-adapt' it with practice (Bastian, 2008).

A good example for adaptation and de-adaptation is a 'backwards' bicycle (Sandlin, 2015), i.e. one in which turning the handlebar to the left makes the wheel go to the right, and vice versa. So, riding the backwards bike require adaptation of balance and postural control in a totally opposite way to normal. In the video of this experiment, riders struggle with their balance and fail to progress even a few meters. The inventor of the backwards bike, Mr. Sandlin, reported that he learned to ride it in eight months, while his six year-old son took only two weeks. Both father and son were used to ride 'normal' bikes, but the son adapted to utilizing 'backwards' bike much faster because of higher level of neuroplasticity during childhood. Once adapted to the backwards bike, Mr. Sandlin reported that he had difficulty of de-adaptation to normal bike again and needed to practice (Sandlin, 2015). Sensorimotor adaptation and de-adaptation processes are probably more experimented in astronauts. Astronauts are unique group, exposed to microgravity and disrupted sensory information during their mission in space. The nervous system must organize sensorimotor information in space and reorganize it upon arrival to Earth. Astronauts face deficits of perceptual and motor functions on return to Earth. The average de-adaptation time for functional mobility of astronauts following six-month stay in space was found to be 15 days (Mulavara et al., 2010). Recent research in this field attempted to enhance sensorimotor adaptability through training that is dependent on practicing sensory variations of the task (Bloomberg et al., 2015). In this practice, astronauts use a special treadmill, whose walking surface can be manipulated to provide challenges to gait stability. Also, discordant visual stimuli is provided by a virtual visual scene, ensuring that gait and posture need to be adjusted to several sensory variations (Bloomberg et al., 2015). In this and similar attempts, the ultimate aim is learning to learn, in other words, to train nervous system to adapt to changing situations faster and more efficiently.

Stages of motor learning

All of those who are introduced a novel skill are very naive at the beginning, but improve their performance with practice. In the skill acquisition process, we observe differences of the following performance characteristics: improvement, consistency, stability, persistence, adaptability, and reduction of attention demand (Magill and Anderson, 2007). First of all, over period of time, performance improves. Second, as learning progresses, we see a more consistent and stable performance from one trial to another. Persistency describes the capability of showing improved performance over increasing periods of time; e.g. days, weeks or months. Adaptability or generalizability is an important aspect of performance related to skill learning. It refers to adaptation to changes in personal, task, and/or environmental characteristics. Lastly, motor learning leads to reduction in attention demand, allowing an individual to show dual-task performance, such as conversing while juggling balls.

Most of the motor tasks require optimization of both speed and accuracy. For experts such as professional athletes, the goal is to perform a task as quickly and accurately as possible. According to the well-known Fitts' law, movement time (speed) can be predicted when the distance to the target, and the width of the target are known (Fitts, 1954). The formula of Fitts' law is $\mathrm{MT} = a + b^{*}\log_2 (2\mathrm{D}/\mathrm{W})$. Movement time (MT) scales as a logarithmic function of the ratio of movement distance (D) to the target width (W), where ***a*** and ***b*** are coefficients.

Derived from the Fitts' law, there is speed-accuracy trade-off, which defines the decrease in the movement speed when the task requires more accuracy; for example, to thread a needle, a certain degree of slowness is needed to push the thread through the eye. If you speed the movement up, the thread would target a larger target area, as can be derived from the formula. The question is whether Fitts' law holds its predictive value during motor learning, since during learning, movements become faster and more accurate while target distance and target width remain the same. The answer is that Fitts' law is still found to be valid, but with changed coefficients (Latash, 2012).

The distinct stages of motor learning have been defined by certain models. Despite different terminology and stages defined, all models essentially agree on the main characteristics of the learning process. Below, the models are briefly described.

Fitts and Posner three-stage model proposes a process of cognitive, associative and autonomous stages. This model highlights that in the early stages of learning there is much higher cognitive demand, such as problem solving, working memory and attention until the skill becomes automatic (Magill and Anderson, 2007).

Bernstein's three-stage model focuses on the changes in motor control in consecutive stages of motor learning. In order to understand his theory, it is important to understand the degrees of freedom problem. The number of independent components and how each component can vary creates numerous degrees of freedom for the motor system. For example, in order to reach object, many muscles and joints have to be controlled by the nervous system. During motor learning, Bernstein suggested that the motor system has to solve this problem. At the first stage, he proposed an inhibitory pattern that there is an elimination of, or *freezing, redundant degrees-of-freedom* to simplify the control of the movement. In the second stage, control becomes more comfortable, which is associated with *releasing degrees of freedom* that were previously frozen. In the last stage, there is an *optimal interaction with external forces* that leads refinement of control strategies, meaning that a person learns to use, rather than fight against external forces (Latash and Turvey, 1996). Bernstein's model was experimentally supported; a recent finding in transtibial amputees confirmed the freezing and releasing stages during lower limb joint flexion and extension (Wurdeman et al., 2014).

There is also a two-stage model proposed by Latash, which relies on the changes of motor synergies. According to this model, variance of performance characteristics can be viewed as having two components; *good* and *bad variance* . In the first stage, bad variance decreases while good variance shows almost no change, which strengths the motor synergy. In the second stage, bad variance decreases as much as possible, while good variance decreases to the optimum level, which weakens the motor synergy. With practice, bad variance decreases so, for example, accuracy of performance increases (Latash, 2012).

Ann Gentile proposed another two-stage model with a perspective on the learner's goal. In the *initial stage of learning* , movement pattern is acquired and the conditions in the environmental context are learned and identified in order to achieve the action goal. In *later stages*, she highlighted improvement in three characteristics of the action: adaptation, consistency and economy of effort. She also proposed that learner's goals depend on the type of skill practiced (Gentile, 1972). In *closed skills*, learner shows fixation on the movement pattern learned in the initial stage, and refines it to achieve consistency and economy. An example of a closed skill is writing with the same type of pen on the same type of surface. *Open skills* require the learner show diversification of the basic movement pattern learned in the initial stage, thereby motor adaptation. Gentile's perspective provided a framework for goal-directed training for rehabilitation settings (Mastos et al., 2007).

The final model is Halsband's three-stage model, defined in neuropsychological terms as follows: In the *initial stage*, performance is under close sensory guidance, and the accuracy and speed of performance varies greatly from trial to trial. In the *intermediate stage*, sensory-motor connections become stronger; movements become faster, and more accurate, and are executed with smaller variance. In the *advanced stage*, performance is fast, automated, and skillful, with isochronous movements and whole sensory field control (Halsband and Freund, 1993). Halsband's model was demonstrated in a study where individuals were trained with auditory information for reach-and-grasp task. This task was designed to give auditory information regarding the size of the objects to grasp to allow individuals to establish a new audiomotor map. They found no overt signs of learning in the first approximately 10–15 trials; subjects used the maximum grip aperture to achieve the task. This was followed by a period of fast learning, where individuals adjusted the hand grip according to the size of the object via auditory information, and in the final stage they reached a plateau of learning (Säfström and Edin, 2006).

Learning skill in different life stages

Not all behavioral changes result from learning. Phylogenetic memory was shaped during evolution, and results in some innate behavioral responses, such as fear. Recent study in mice showed the strong memory traces of fearful experiences in subsequent generations. Fear response to conditioned odor was found to enhance neuroanatomical representation of the odor in the brain and, more importantly, this was selectively transmitted to next generations (Dias and Ressler, 2014). What about human behaviors? How much genetics and experience contribute to learning? This question touches the controversy of the effect of ‘nature versus nurture’ on development. Developmental studies, especially on infants, have investigated whether genes predetermine motor development, or whether it is a result of practice and interaction with the environment.

According to the developmentalist Gesell (1934) motor development or acquisition of motor skills such as rolling, sitting, standing, walking appear in a sequence and within specific periods during infancy, emphasizing the role of genes in unfolding development of motor skills (Gesell et al., 1934). On the other hand, recent dynamic systems theory suggests that motor development is not a simply passive process in which genes dictate the developmental milestones over time. Rather, infants actively perceives and acts upon the constraints set by their bodies and environment to achieve a goal. Therefore, according to other developmentalists, infants assemble motor skills for perceiving and acting (Keen et al., 2014). However, experiments such as the “visual cliff”, suggest that infants are born with depth perception that directs their motor skill acquisition (Feldman and Garrison, 1993).

Myelination is very important for motor skill development during childhood. Training or practice during childhood has very prominent effects on myelination. Motor practice induces the neural activity in fiber tracts, and therefore induces myelination. In a study by Bengtsson et al., in which they compared the neural correlates of extensive piano practicing during childhood, adolescence and adulthood, they found regional specific changes in pyramidal tract. Most importantly, largest number of brain regions correlated with childhood practicing, even compared to much more intensive practice in adulthood. This example explains the interaction between nature and nurture, and indicates a developmental window in which white matter plasticity is highly favored (Bengtsson et al., 2005).

Older adults is another group for whom it is important to consider for motor learning. Increase in aging population and longer life expectancy in many countries highlight the motor learning capacity and plasticity in this group. With increasing age, musculoskeletal and nervous systems, and sensory organs are negatively affected. Seeing, hearing, touching are important sensory functions for motor system, and decline in these sensory functions are significant in individuals 75 years and older (Santrock, 2006). According to a study, older adults take longer to move than young adults, and this difference remains for both easy and difficult movement tasks (Ketcham and Stelmach, 2001). With these information, it is no surprise that perceptual-motor coupling is declining, and leading problems for already learned motor skills such as driving (Santrock, 2006). On the other hand, learning new motor skills is intact, but with a slower rate. In a study, six days of training in a novel task, juggling, with participants aged in 6 to 89 years showed the performance of older adults was comparable with those of children and young adults. The study showed the best outcome for teenagers and young adults between 15 and 29 years (Voelcker-Rehage and Willimczik, 2006).

Motor learning in expertise

Experts are a special group of people who develop skillful actions above the level of normal performance. The area of expertise can be in cognitive domains like science, mathematics, chess-playing, or in motor domains such as athletics, piano playing or ballet. There are some key characteristics of experts. First, they deliberately practice the skill for extensive periods. Second, they have a strong interest in the skill, and thereby, motivation. Lastly, they prioritize skill training over other significant daily life activities. In motor learning, experts are a valuable group for investigating enhancement of performance of a learned or highly experienced motor skill.

Musical expertise in piano players has been extensively studied by Fredrik Ullen’ s research group. They measured the amount of practice (total hours of practice) during different developmental periods; childhood, adolescence and adulthood, both in piano players and in nonmusicians. Longer practice time and white matter changes were found in all groups, regardless of age. Age was generally found as a strong predictor for brain development. However, this finding may show that practice may hinder the age-development relationship (Bengtsson et al., 2005). Macro anatomical changes have been observed in musicians. Increase in cortical gray matter volume and higher fractional anisotropy in white matter have been reported. These changes have been shown in the corpus callosum, motor cortex, cerebellum and planum temporale of musicians (Schlaug, 2015). Cortical excitability has also been shown after long-term motor training; musicians showed less interhemispheric inhibition (Nordstrom and Butler, 2002).

Expertise in professional athletes has been one of the most intriguing areas in the field of motor learning. Recent technological advances in methods to study kinesiology provided valuable data. Video-based analysis of technical movements showed that famous football player Lionel Messi makes more use of dribbling and feint of change of direction than Cristiano Ronaldo, meaning that Messi showed variability, and was more unpredictable (Castañer et al., 2017). It has been shown that humans predict others’ actions by using bell-shaped velocity profile (Stadler et al., 2012). However, data that movement of Messi is unpredictable, i.e. he does not fit into this bell-shaped velocity profile. A study by Anderson and Sidaway showed that as an acute result of practice, novice soccer players increased linear velocity of the foot in relation to changing pattern of coordination underlying the movement (Anderson and Sidaway, 1994). Trial-to-trial variability in the execution of movements is usually considered a drawback of the noisy sensory motor system, however, recent studies have suggested that motor variability may also be a feature of how sensorimotor systems operate and learn. This view stems from the reinforcement learning theory, and sees motor variability as purposeful exploration of motor space that can drive motor learning (Dhawale et al., 2017).

The variable practice, rather than repeating the same task, is favored in athlete training programs (Li and Lima, 2002; Shoenfelt et al., 2002) because sensorimotor adaptation leads to a high level of plasticity and learning effect, which in effect teaches the system to learn to learn. Schmidt's schema theory of motor learning suggests that the motor system creates a library of motor actions (schemas) for classes of motor problems (Schmidt, 1975). In each trial, the performer stores the initial condition, specific surrounding, sensory consequences and the outcome of the movement. Over trials, varying conditions of practice allows the motor schema to become optimized. When a novel motor task is presented, the person, if trained with variable practice, is able to retrieve the appropriate movement patterns more efficiently (McCracken and Stelmach, 1977; Shea and Morgan, 1979; Catalano and Kleiner, 1984; Sherwood, 1996).

Another focus in athlete training has been on whether implicit or explicit processes lead superior performance, and accordingly, which components of performance benefits. It has been found that implicitly learned motor skills tend to be stable under performance pressure (Hardy et al., 1996; Mullen et al., 2007) and physiological fatigue (Poolton et al., 2007; Masters et al., 2008), and also demand less attention (Maxwell et al., 2003; Poolton et al., 2006). Due to difficulties in designing experiments involving implicit and explicit learning, there are only small number of studies. In one study (Lam et al., 2009), in modified basketball shooting task, three groups were compared after receiving three-day training. The first group received explicit learning via eight technical instructions, the second group received implicit learning via single analogical instruction, and the final group received no instructions. No performance differences were found between groups in retention tests, indicating that there was no difference between learning models. However, in transfer test, despite the lack of any kinematic changes, performance deteriorated for both explicit and control groups, but not for the implicit group.

Disability of motor learning

Disability of motor learning can be seen in diseases that affect nervous and musculoskeletal systems, and sensory organs. More intriguingly, it can be seen during childhood development without any apparent physical or intellectual problem. Developmental Coordination Disorder (DCD) is one of these developmental disorders. In DCD, children fail to learn complex coordinated movement skills, such as riding a bike, or handwriting. Motor learning problems recently proposed as an explanation of co-occurence of neurodevelopmental disorders such as ADHD, dyslexia, language impairment and DCD. The "procedural deficit hypothesis" suggests that commonly observed clumsiness and learning deficits in these mildly effected groups are results of procedural (or motor) learning deficit (Nicolson and Fawcett, 2007). We use the motor learning system to acquire the movement patterns to produce speech sounds and motor actions. During development, most affected by motor learning deficit are speed and accuracy of manual movements during complex task, e.g. drawing or handwriting, and articulation of complex speech sounds. Attention mechanisms are known to be important in the initial phase of motor learning. Consequently, impairments in speech and motor domains, which require learning of complex sequence of movements, are commonly observed in neurodevelopmental disorders. Childhood Apraxia of Speech is considered as a neurodevelopmental disorder that exhibits the deficit in motor learning, because affected children showed lower performance both in speech and complex manual skills such as drawing (Tükel et al., 2015). Autism Spectrum Disorders (ASD) is another group with defined motor learning difficulties, despite the absence of any brain lesion or malformation (Ming et al., 2007).

Motor learning in rehabilitation

The primary goal of rehabilitation is to induce neuroplasticity from cortex to spinal cord for restoring motor and cognitive skills. Motor learning principles are used in the rehabilitation context to facilitate neuroplasticity and motor recovery. Experiments in healthy subjects highlighted that practicing the task under varied sensory stimuli, rather than repeating the same task in stable conditions, leads to better outcomes that can be described as faster adaptation (Roller et al., 2001). This means that the sensorimotor system learns to adapt to changing conditions better, in other words, the system is more plastic. This principle has been transferred to therapeutic approaches in Down syndrome (Latash et al., 2002), and to neurorehabilitation of stroke patients (Krakauer, 2006).

Rehabilitation programs in stroke patients showed the potential variation in groups with different severity of dysfunctions. In a study by Hardwick et al. 4-day training was given to stroke patients and healthy controls. Stroke survivors were divided into two groups according to motor impairment: mild-to-moderate and moderate-to-severe. Groups practiced isometric contractions of elbow flexors to navigate an on-screen cursor to different targets for 4 days. The speed-accuracy trade-off function was assessed for each group before and after the training, and controlled for differences between individuals in self-selected movement speeds. All groups were able to improve their performance through skill acquisition. The moderate-to-severe group reached the baseline performance of the mild-to-moderate group, and the mild-to-moderate group reached the baseline performance of the control group (Hardwick et al., 2017). Robot-assisted therapy seems to have strong potential for improving upper limb function in stroke patients. It was shown more effective than usual care when applied for 12 weeks and 36 weeks; however, intensive therapy outperformed robot-assisted therapy (Lo et al., 2010).

There is a greater amount of research on motor learning during development in the case of brain lesion in children with cerebral palsy (CP) conducted by Ann-Christin Eliasson's research group. Sensorimotor reorganization of the central nervous system, in case of early brain lesion, shows an impressive capacity for compensation and preservation of functional motor skills. In unilateral CP, contralateral corticomotor projection pattern was found important for the speed and accuracy of reaching, grasping, releasing and functional tasks (Holmström et al., 2010). Two weeks of motor training with constraint induced movement therapy (CIMT) improved manual skills irrespective of corticomotor projection pattern and brain lesion characteristics (Islam et al., 2014). Motor learning of handwriting skill has also been investigated in children with unilateral CP, and findings indicated a slower rate of learning in motor skill acquisition, which can be predetermined by chronological age and IQ score (Fig. 25.3) (Tükel Kavak and Eliasson, 2011).

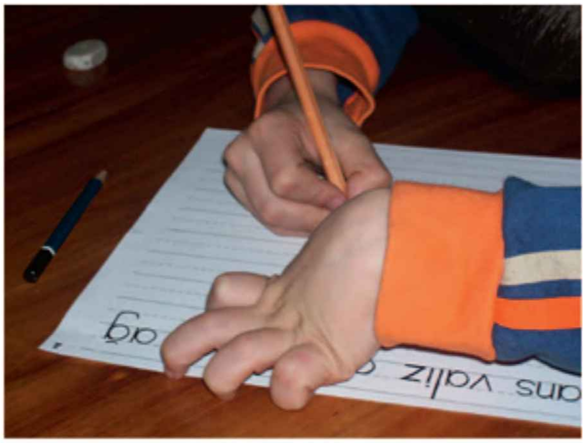

FIGURE 25.3 A child with unilateral cerebral palsy (CP) is shown during handwriting test. Learning handwriting refers to copying readable letters therefore; it requires speed and accuracy of fine motor movements along with visual perception and visual working memory. Children with unilateral CP usually use their non-effected hand for handwriting while using their effected hand to stabilize the paper as shown in the picture. Motor learning of copying readable letters take longer time period for children with CP compared to those of their typically developing peers. Learning rate in CP group can be predicted by age and IQ.

Observational learning and the so-called 'mirror neuron system' has become one of the most promising approaches in rehabilitation. During the last decade, various studies were carried out regarding the clinical use of action observation for motor rehabilitation of sub-acute and chronic stroke patients. Mirror neurons are a specific class of neurons that are activated and discharge both during observation of another individual's motor act, and during the execution of the same or similar motor act (Rizzolatti et al., 1996). By using TMS and fMRI, different studies have demonstrated the presence of the mirror neuron system and their mechanism in humans. Studies have demonstrated the activation of brain areas involving inferior parietal lobe and the ventral premotor cortex, as well as the caudal part of the inferior frontal gyrus, when individuals learn motor actions via execution, imitation, observation and motor imagery. This means that observing or imagining an action can affect cortical excitability and facilitate subsequent movement execution. The intention to imitate movements shown on a video resulted better outcome for functional upper limb dexterity for stroke patients (Franceschini et al., 2012). Similarly, for Parkinson's disease, imitation of motor actions seems a promising rehabilitation tool (Caligiore et al., 2017). In healthy individuals, observational motor learning has been found very effective for implicit learning of sequential complex motor skills. Findings from SRT task showed that subjects can acquire sequence information by watching another person performing the task, and observation results in as much sequence learning as task practice. This study also showed that sequence knowledge acquired by model observation can be encoded motorically (Heyes and Foster, 2002).

Since 1994; when Salinas & Abbot showed that the direction of resulting limb movement can be computed from measurements in fewer than 100 primary motor cortex cells (Salinas and Abbott, 1994), the activation of primary motor cortex has been used to guide prosthetic limb in prosthetic rehabilitation, suggesting applications for patients with amputated or paralyzed limbs. One study demonstrated that two tetraplegic patients could exert some control over the speed and direction of movement of a computer cursor based on recording of 96 neurons in the dominant hand area of the primary motor cortex (Kim et al., 2008). In a more recent study, Hochberg et al. showed that tetraplegic patients are able to move a robotic arm for reaching and grasping, and in one case, use the robotic arm to drink from a bottle (Hochberg et al., 2012). Of course, there are high levels of variation between individuals in these experiments. The impressive finding is that individuals show neuroplasticity and can learn to fire their motor neurons to control the robotic arm.

In rehabilitation setting, studies also highlight the strong relationship between motor learning and emotional and motivational factors, thus are often use the words 'goal-directed' or 'targeted' to describe a movement, because all movement has an aim. Motion, cognition and emotion are interconnected, faster and more efficient motor learning can be facilitated by motivation and cognition. This interaction is well-known by clinicians working with patients during the recovery phase, but without tools to motivate the patients, is often overlooked. It is important to emphasize that rehabilitation settings require either interdisciplinary teamwork, or interdisciplinary-equipped clinicians who can develop therapeutic approaches that fuel motion-cognition-emotion interaction.

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Chapter 26

Balance and postural control

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Definition of balance and posture

Balance and Postural control: what is the difference?

In many occasions the words "balance" and "postural control" are used interchangeably. Especially, in the clinical setting the term "balance" is more frequently used. There are several clinical tools (for example; Berg Balance Scale) commonly used to assess balance. Most of these tools are subject to debate in terms of their sensitivity, cut-off points, validity and reliability when they are used for evaluating balance in several different kinds of clinical conditions. However, when it comes to quantifying balance, in other words when quantitative data is needed concerning the properties of human balance, the term "postural control" is often preferred.

For example, close to the end of her performance (flips, soars and swings) an artistic floor gymnast skillfully demonstrates a static stance on both feet with arms wide open in a posture that salutes everyone. In this way she demonstrates how well she has trained over the years and presents the level of control she has mastered over her posture. The very moment she stops moving and begins her static stance, the saccule and the utricle in her middle ears should measure zero acceleration in both horizontal and vertical planes. Also, the movement of the fluid in the semicircular canals, measuring head rotation in three planes, should stop tickling the hair cells placed in cristae. However, they do not. The biological sensors, in this respect, are far from man-made. They do not stop immediately and continue on sending data. In this gymnast case, the data tells the brain that the head is still accelerating linearly in both horizontal and vertical planes and is also rotating with respect to the trunk. In addition, the visual data provides some ques about the cheering audience but they seem to be moving fast and resonates as a colorful mixture. The brain, however, relies on a different kind of information obtained by the somatosensory system which insists that the movement has ceased, except some ongoing regular pattern of Center of Mass (CoM) sway. In this example the referees (among many other technical details) score the performance and the level of perfection related to the dynamic and static balance of the gymnast. They do not score the level of her control over postural data. They do not praise her success in automatic distinguishing and re-weighting the most reliable data among many others provided by her visual, vestibular and somatosensory systems. They just score what they have seen: human balance. In conclusion, although these two terms can be used interchangeably as appropriate, the human balance may be re-defined as the clinically observable outcome of the human postural control system.

Geocentric reference frame

For each and every functional task, the orientation of body segments with respect to each other and to the environment is an important point. For this reason, the preparatory neural mechanism driving the motor system gathers data from many perceptive systems to acquire the necessary references related to body position. Successful representation of the body, head and extremities in a three dimensional environment depends on this critical postural orientation. Thus, posture is a short and key term defining any reference position in which body segments are aligned to form a baseline orientation that the neural system accepts as a starting frame for any function. Although different activities may require different postures, the simplest and basic human posture is usually accepted as upright standing. In upright standing the segments have to be positioned in the presence and against gravitational force. In other words the pull of the gravity along a vertical axis forms a reference resistance against which all the

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body segments are positioned by using extensor muscles. In general this axis and the resultant posture is referred to as geocentric reference frame.

Although the recent research seems to focus on sensorial inputs and their effects, weighting and internal integration on upright standing, to date no study has clearly denied the presence of reference frames (Ivanenko and Gurfinkel, 2018; Ishikawa, 2016)

Center of mass, center of gravity and center of pressure

Center of mass (CoM), center of gravity (CoG) and center of pressure (CoP) are the three terms commonly used while studying on postural control and related mechanisms. Thus, one should need to know the difference and the relation between the three. CoM is defined as the point where the distribution of mass of a given object is equal in all directions. The mass of an object does not change in different gravitational constants. CoG has a similar definition but this time the distribution of the weight of a given object should be equal in all directions. It is obvious from the formula (W=m.g) that CoG and CoM are not synonyms as CoG may likely to change depending on the gravitational constant. The CoG in humans would be placed in higher position if the strength of the gravitational field was not uniform and applied more force to you 2 m high above the ground. Still, as the gravitational pull of the earth is uniform and changes slightly even if the altitude is 10 km off the ground, the points of CoM and CoG coincides well on earth. This is the reason why they are used interchangeably.

CoP is the point where the sum of the gravitational reaction forces are applied to the object. Measuring CoM can be time consuming and expensive due to the necessity that in order to calculate CoM, mass of the every segment of the object and their position in three dimensional space should be obtained (Winter, 2000). Instead, in most research, CoM is derived out of the data related CoP as an estimate (Benda et al., 1994). There are several ways to estimate CoM from CoP data which are beyond the scope of this chapter. However, simple facts about the movement and the relation between CoM and CoP should be known. In fact, if every segment in the body is expected to be totally still and not even a slightest of a movement occurs, it is possible that CoG coincides with CoP. However, it is not possible. Even during quite standing the human body sways. One should keep in mind that it is the CoM that should be kept in boundaries (support surface). Thus, CoP acts faster (in higher frequencies) to control CoM. It is obvious that directly controlling CoM in static standing is impossible due to the fact that you cannot change the position of the body segments while standing still. On the other hand, CoP can easily be controlled by active force generation of the muscles (i.e. dorsiflexors) without kinematic changes detectable by common tracking systems (for example motion capture cameras). When a perturbation is introduced to human body during static standing the CoM moves towards in the same direction of the force applied by the perturbation with a proportionate velocity. In order not to fall down, the CoP moves faster than the CoM, gets past to it and then brings it back so that the system turns back to the original state of dynamic equilibrium. This means that CoP movement pattern is an estimate of the magnitude of the CoM movement pattern with a neglected delay. Thus, it is an indirect measurement of CoM. Indeed, in a simple graph regarding the displacement of CoM and CoP in relation to time, it is obvious that although there is a time gap (lag) between the initiation of movements, CoP is much faster than CoM and works in higher frequencies. In this manner, CoP restores balance. However, it is important to keep in mind that, in dynamic situations the CoM and CoP do not necessarily coincide.

Introduction to integrative models to human postural control

For the objects that are regular in shape, homogenous, motionless and not alive, definition of balance is easy. When these objects are not affected by external or internal forces their CoM usually coincides exactly with CoP which does not change under fixed circumstances (Fig. 26.1). However, human body is irregular and also is under constant perturbation caused by internal and occasionally external forces.

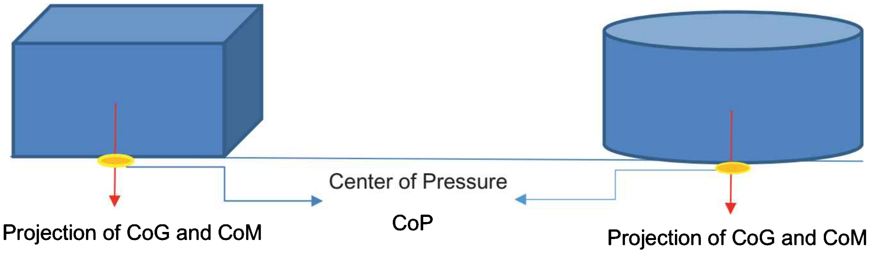

FIGURE 26.1 The projection of CoM and CoP coincides exactly at the same point in regular shapes. This point also serves as the CoP. Thus, the system is in constant equilibrium if no internal and external forces are applied.

Above explanation indicates two fundamental rules about human postural control. First, human body is not stable, and second, in order to understand how it is stabilized under static or dynamic conditions, we need to model the sequences of the process called postural control.

Sensory-motor background of balance and postural control

Models of postural control

Most models so far, related to human postural control, have studied upright standing position. In this position, many aspects related to static standing (CoP sway velocity, CoP length, CoP sway area etc.) have been investigated. Interestingly, although the investigated position is accepted to be static, the very nature of the relation between CoM and CoP explained in short previously, indicates an equilibrium which is dynamic. Through this text, keep in mind that even though it is implied that a static posture is studied, maintaining human balance or postural control can never be static. In fact, it is composed of many processes regulating the dynamic relation between CoM and CoP.

The very classical approach in defining postural control relies on sensory systems: visual, vestibular, proprioceptive and somato-sensorial (tactile). In over a hundred years, a lot of research have been dedicated to the mysteries of postural control. As previously expressed, in early studies the reference frame (reference posture) was thought to be determined genetically (Magnus, 1924; de Kleijn, 1924). Therefore, the overall postural control was thought to rely on postural reflexes (more often they were called postural reactions) which were dependent on and modulated by the above mentioned systems. However, in early 1990s, it was realized that this simple model of postural adjustment was not even close to the actual complexity of the neuro-motor control and sensorial integration behind postural control (Massion, 1994). Indeed, postural control was in need of postural reflexes but it was understood that the control system included anticipatory reactions (Patla et al., 2002). It is also capable of comparing the measured (actual) and the predicted (forecast) data and demonstrate integrated behavior. In addition, it is definitely able to decide the importance (weight) of a given sensorial data, compare it to the predicted (prior experience), double-check with the other systems data and attribute a new weight (re-weight) to that data much like in the example of the gymnast (Ishikawa, 2016; Asslander and Peterka, 2014).

There are numerous studies some of which using actual data and some others controlled models (Wearing et al., 2013). Still, a complementary model is yet to be established. However in this chapter, instead of complicated theories and related models, we will try and explain the basic concepts.

Balance maintaining strategies

CoM and CoP behavior during quite standing - the past and current concepts summary

In a mechanical perspective of view, all mechanical systems try and increase their entropy while preserving a minimum energy state which in humans can be achieved by lying down. However, one of the greatest differences of humans from other terrestrial mammalians is the energy efficiency during most bipedal functions, especially in standing and walking. The efficiency in bipedalism comes from the delicate interaction of human postural control system with internal (e.g.muscles) and external (gravity and ground reaction) forces (Bouisset and Do, 2008).

Generally, in quite bilateral standing, the projection of CoM falls in the base of support and sways in a chaotic path (Fig. 26.2). The amount of sway is small (1°–2° of joint movements or 0.5–1 cm of oscillatory movement) as long as there are no other conditions that would likely to alter the postural control (Winter et al., 1998). In this position, according to Winter et al., the stiffness model that assumes the body as an inverted pendulum and resembles the whole system to a mass, spring, damper system, works fine. They concluded that as the base of support increases the sway amplitude decreases along with an increase in total stiffness of the system. Furthermore they reported that a reactive postural control was not evident as there was no difference in eyes closed and eyes open conditions. In their model, there were also no head and joint movements that would cause vestibular and proprioceptive systems to react. In addition, they hypothesized that any reactive control would cause a considerable delay (a lag of 150–250 ms) between CoM and CoP movements. However, they have shown that the actual lag between CoM and CoP was only 4 ms and CoP was almost phasic with CoM movements. They attributed these results to the passive dampening of the mechanical system designed as an inverted pendulum that would likely decrease the output of central nervous system.

Indeed, the stiffness of inverted pendulum model seem to explain many aspects of postural control in quite standing. In this respect, the study of Winter et al. has given rise to numerous studies investigating postural control by altering sensory inputs and observing the behavior of CoP (Loram et al., 2007; Sakanaka et al., 2016). However, all these methodological approaches, accepting the whole system as linear, seem to be missing the non-linearity in biological systems. Ivanenko et al, in their review in 2018, pointed out to the several evidence in the relevant

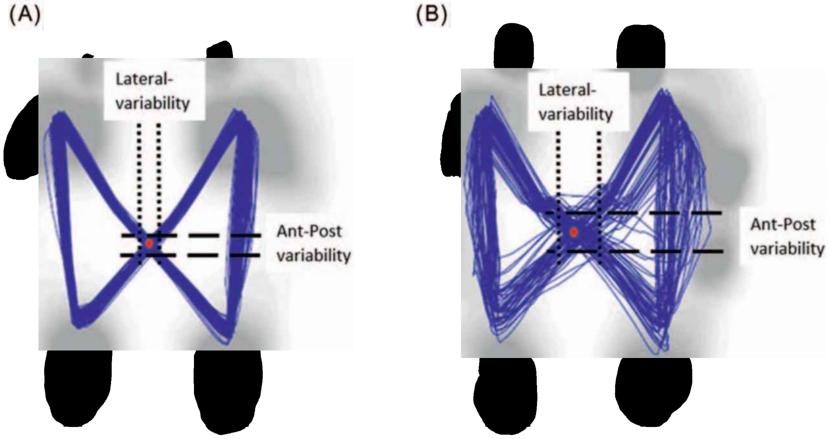

FIGURE 26.2 A butterfly diagram derived from the instrumented treadmill.
Gait variability parameters derived from the butterfly diagram. Red dot indicates the intersection point of the center of pressure trajectory during walking. Dashed lines represent CoP variability in A-P and lateral directions. (A) Healthy person. (B) Person with MS (EDSS=4.0).

literature indicating that non-linearity exists in postural control (Ivanenko and Gurfinkel, 2018). The muscles and their passive resistance to angular displacement around the ankle joint in the sagittal plane, thixotropic characteristics of the muscles leading to proprioceptive gain, compliance of soft tissues and instantaneous deformation of the foot arch and soft tissues may be counted among these non-linear aspects. For example, according to Gurfinkel et al., in healthy adult individuals the vertical oscillation of calcaneus nearly 0.5 mm causes approximately 0.7 cm of CoP displacement (Gurfinkel et al., 1994).

The clinical relevance

Although debate is going on about on neuro-mechanical control of static and dynamic postural control, investigating CoP behavior in both normal and pathological conditions still holds its place as an important aspect of evaluating balance.

There are many CoP parameters (over 105 so far) which are obtained from stabilometric analyses. In static analysis it is called stabiliogram and in repeated dynamic conditions like walking it is called cyclogram (butterfly diagram) (Fig. 26.2).

Stabilogram/ posturography

A stabilogram defines the evaluation and analysis CoP during static standing under normal, perturbed or altered conditions. Perturbed testing, however, should not be understood as a dynamic condition like cyclogram. It is rather used to test CoP behavior using a dynamic paradigm (perturbation) during static stance. The reasoning behind static and dynamic paradigms is that during static paradigm the most active system gathering data for the central nervous system is the somato-sensorial system (cutaneous mechanoreceptors under the feet) while vestibular and visual perceptions are usually very close or under the firing threshold to be accepted as active for postural control purposes. Furthermore, static paradigm evaluates a more predictable CoP signal that is the resultant of an inherent and built-in model of anticipation (Palmieri-Smith et al., 2002).

As previously mentioned there are several aspects of the analysis that can be performed using CoP signal. In this text, some of the most commonly used parameters (other than spectral analysis) will be presented.

CoP trajectory

Most of the analysis begins with obtaining a CoP trajectory (which is unidimensional) in which CoP sways in many directions. The raw data includes anterior-posterior and medial-lateral movements of CoP which is usually accepted as to represent and coincide CoM movements with a negligible amount of disparity in between the two. Please note that in the previous headings the relative movements of CoP and CoM are discussed briefly. Although it is negligible from a clinical point of view, the debate is still going on and thus, this text remains inconclusive about the contradictory opinions about the relative positions and interaction between CoP and CoM. In fact, CoP sway should be considered as a measure of the overall control of the neuro-motor system and not an exact measure related to the movement of the CoM (Ruhe et al., 2011a). Thus, many authors conclude that especially during static paradigm CoP sway is related to the natural noise of an anticipatory neural control system and the result of this anticipation which seeks to control and maintain the overall balance of the body (Massion, 1994; Gatev et al., 1999; della Volpe et al., 2006). This means that although CoP movement is desirable, CoM movement is undesired. However, to what extent and degree the CoP sway is desirable remains unknown. Due to this fact researchers are under constant debate and conclusions from different research including different populations may be contradictory to each other. Keeping these in mind the following section is prepared just to give an insight to the reader about posturography and the most commonly presented parameters in the literature, with no intention of drawing conclusions related to the topic. The most common parameters used to analyze CoP Sway are presented below.

CoP sway path/CoP total excursion (mm): Sway path is defined as the total length of the distance covered by the CoP over the course of a trial duration. It is important to note that the calculation assumes that CoP is a movement. However, the trajectory actually is formed by connecting the locations of instantaneous CoP points and summing the distance between them (Hufschmidt et al., 1980). It is still under debate that whether an increase in this parameter represents a balance problem or a decrease would likely to be interpreted as a flaw in maintaining overall balance (Palmieri-Smith et al., 2002). The argument is that a fully healthy postural control system may have long A-P and M-L excursions. As there are no strong evidences that point out to the fundamental relationship between total excursion and physiological responses of the motor system, it is not clear that this parameter is a valuable construct in evaluating postural control.

CoP sway velocity (mm/s): Sway velocity is the total excursion over time. Its reliability has previously been shown for double-legged stance (Le Clair and Riach, 1996). A higher velocity may mean that CoP races faster to control CoM. This was previously shown in related research. For example, Prieto et al. demonstrated higher mean CoP velocities with increased age (Prieto et al., 1996). However, the rationale is still somewhat obscure. For example a faster velocity rate may indicate a CoM that is not easily controlled or may reflect a flawless and strict control of a neuro-motor system that never loses control over its CoM under static conditions. On the other hand, a slower velocity rate may be the result of a slow moving CoM which does not require too much attention by the nervous system or a disturbed postural control system that is not able to control CoM properly. Either way the clinical implication of this parameter is unclear (Davids et al., 1999)

CoP sway area (mm^2/s): Sway area is the area which is scanned by CoP trajectory over a given period of time. Sway area constitutes (in most standard testing protocols) of maximum excursions of CoP in eight directions so that by using these data points an elliptic area (including 90% of all excursions data) is derived. It is suggested that the larger the sway area the individual is more successful in controlling his/her balance. It should be noted that the sway area expanding towards one or multiple directions more than the others and resulting in a large sway areas may be a problematic situation. Thus, directional symmetry may be an important point of consideration.

Displacement of CoP - maximum and minimum amplitudes (mm): Another controversial parameter related to the CoP movement is the displacement of CoP. Maximum amplitude refers to the maximum excursion that CoP reaches out from its mean and the minimum excursion refers to the minimum excursion from the same point. Previous research concluded that an increase in maximum amplitude and decrease in the minimum amplitude is indicative of poor postural control and vice versa (Leanderson et al., 1996). However, in a recent study it has been shown that three consecutive trials for the same test resulted in large variation in both area and excursion lengths (Winter et al., 1998; Chaudhry et al., 2011). Since amplitude in A-P and M-L directions and CoP sway area is directly based on multidirectional excursions, it is hard to come to specific conclusions that are indicative of stability in postural control. Another objection related to maxiumum and minimum amplitudes is that they refer to 2 single points that are representative of a set of many points (for example; 3000 points in a trial of 30 s sampled at 100hz). Palmieri et al. concluded that any small perturbation such as a flicker of light may open a sensory loop for a fraction of a second and a resultant large excursion may lead to misinterpretation of the obtained data (Palmieri-Smith et al., 2002).

Mean CoP amplitude (mm): The mean CoP amplitude is the average amplitude of all CoP excursions. Although it is a better projection of balance compared to minimum and maximum amplitudes it has still some flaws in it. The main problem is to determine the starting point of CoP in a trial. As this point is the key to most of the calculations that are going to be performed it may have tremendous effect on the analysis. If this point is accepted as the center of the platform the feet should strictly be positioned in every trial. The studies have shown that the width of the feet, the foot angle and alternating positions of the feet from trial to trial may result in misleading data (Kirby et al., 1987).

Root mean square (RMS) amplitude (mm) and RMS velocity: The RMS defines the displacement of COP around the mean CoP. This measures is calculated as an absolute value. RMS velocity, thus, indicates absolute displacement of CoP around the mean CoP over time. Decrease in these parameters may indicate that the CoP is somewhat more stabilized in an absolute range around the mean CoP. RMS amplitude and RMS velocity have less debate over them compared to above mentioned parameters. For example, intra-subject over a five week period was shown to be consistent by Guther et al., followed by another study conducted by Le Clair et al. who have reported that during double-legged stance A-P and M-L intersession reliability were R=0.86 and R=0.81, respectively (Geurts et al., 1993; Michalowska et al., 2005).

Balance and posture in pathological conditions

As the healthy postural control mechanism in humans is maintained through the interaction between nervous and musculo-skeletal systems, any pathology causing these systems to malfunction and/or react abnormally causes postural control deficits. Due to this fact, it is not possible to cover all pathologies affecting human postural control in a single supplementary chapter. However, it would still be useful to mention balance related problems and their rationales in some common conditions.

Parkinson's disease

In Parkinson Disease (PD) 55% of the falls were found to be associated with unstable posture and loss of postural reflexes as reported by Factor et al. (2011) and Michalowska et al. (2005). One of the main reasons of this unstable posture is caused by the disease itself. As PD progresses base of support gets narrower, flexor tone increases especially in the lower extremity and a classic stooped posture is obtained (Schoneburg et al., 2013). There are several theories as to why this posture is favored in PD including deformity development, inaccurate verticality perception and increased flexor tonus (Horak, 2006). Even, Mancini et al., in their study conducted on untreated individuals with PD by using accelerometers, found that lower trunk showed increased "JERK" which is an indicator of the sommthness of sway trajectory, in eyes open condition (Mancini et al., 2011). In another study, Stylianou et al. concluded that compared to age matched control individuals with mild to moderate PD demonstrate increased sway path, sway area and max excursion in M-L directions. The result related M-L excursions were later supported by Nantel et al. Nantel et al. (2012). They also advocated that during off-medication as the severity of the disease increases postural sway increases. Schoneburg et al in their review also pointed out to an interesting result related to levodopa. It seems that using levodopa increases postural sway and thus a part of the increased sway in individuals with PD may be attributed to dyskinesia caused by levodopa. Ashburn in their study concluded that usage of levodopa is associated with falls in PD as a condition specific factor (Ashburn et al., 2001).

Multiple sclerosis

According to a recent research the balance problems in Multiple Sclerosis (MS) are mainly caused by conduction and integration problems rather than the lesions in cerebellum. Thus, for example Cameron et al. advocate that individuals with MS try to increase their magnitude of response for a given perturbation (Cameron et al., 2008). It is a logical assumption that the distorted proprioceptive feedback and several problems in integrating these inputs and using them for reasonable outputs are the main causes of increased fall risk in individuals with MS. Furthermore it has been also shown by Fling et al. that impaired ability to control balance was associated with decreased white matter integrity of the cortical proprioceptive tract (Fling et al., 2014). Commonly the research indicate a longer CoP trajectory in individuals with MS which also correlate with clinical assessment related to fear of falling (Kalron et al., 2016). Furthermore it was also postulated that as the disease progress the measures of balance using CoP trajectory worsens with the most significant change occurring once an individual reaches a score of 3 in EDSS score.

Stroke

Following stroke an individual is affected in several aspects that are related to postural control such as impaired muscle tone, sensory integration deficits and cognitive problems which are closely associated with the extent of the damage to the brain. More clinicians tend to use instrumented postural control assessment techniques due to ceiling effect commonly seen in clinical assessment tools. It is well-known that after stroke individuals have increased postural sway and show asymmetrical weight bearing patterns during quite standing (Gasq et al., 2014). However, as most individuals show marked asymmetry, parameters like CoP sway area and M-L excursions are not recommended measurements in evaluating postural sway. According to the Gasq et al. in assessing postural sway in individuals with stroke velocity of CoP should be taken into account rather than CoP area and CoP M-L excursions. In another study, Sawacha et al. demonstrated the relation between clinical and instrumented tools assessing balance following stroke concluded that only some of the parameters indicate a correlation with the clinical tools that are commonly used.

Non-of specific low back pain

Since balance is the basis of all voluntary motor skills, it has been the subject of research on musculoskeletal diseases. Low back pain is one of the most common health problems and affects 80–85% of people over their lifetime. Nonspesific low back pain (NSLBP) is caused by problems in mechanical alignment of the body, which is not related to any other pathological condition such as disc herniation, spondylosis.

There are several theories about the effect of NSLBP on postural stability. Patients with NSLBP have been told that hip strategy will be used less and postural stability difficulties will be experienced due to increased body muscles activation (Mok et al., 2004). Another theory is that the trunk or lower extremities may affect postural stability if the sensory tissues are damaged in the lumbar spine. The muscle afferents as well as affecting the central modulation of proprioceptive spindles of muscles, cause prolonged latencies by the decrease in muscle spindle feedback. These alterations may lead to decreased muscle control and result in increased postural sway (Ruhe et al., 2011b).

In the literature, there are studies showing the changes of the printing center (COP) while people with NSLBP. For example, several studies report that COP is more posterior to control pain in people with NSLBP (Nies and Sinnott, 1991; Mientjes and Frank, 1999). The reason for this may be the adoption of a lordotic posture to relieve pain (Mok et al., 2004). Ruhe et al. stated that participants with NSLBP exhibited an increased sway area compared to healthy controls (Mientjes and Frank, 1999). Also in patients with NSLBP showed an increased the AP direction. Additionally, a higher COP sway velocity was found in NSLBP cases. Kuukkanen and Malkia undertook a study evaluating the changes of postural sway after 3 months of therapeutic exercise. They found no changes in the amplitude of sway but mean total velocity increased significantly in one of the study groups with NSLBP (Kuukkanen and Mälkiä, 2000).

Anterior cruciate ligament rupture

Rupture of the anterior cruciate ligament (ACL), which is frequently seen in athletes, is a musculoskeletal disorder affecting postural control. The ACL is proposed to play an integral role in the central somatosensory feedback loop by providing information regarding knee joint position and movement. Rupture of ACL is postulated to disrupt neural feedback mechanisms and as a consequence has a substantial effect on motor control at the knee (Kuukkanen and Mälkiä, 2000).

Mohammadi et al. showed that the postural control of the athletes with ACL reconstruction was dislocated more on the operated limb than on the non-operated side and matched limb of control group (Mohammadi et al., 2012). The same pattern of findings was obtained such as the studies of Bonfim et al. (2003) and Dauty et al. (2010), which showed that ACL-reconstructed subjects had greater displacement, velocity, area and total distance in the ACL-reconstructed lower limb in comparison with the contralateral limb and matched limb of controls. Culvenor et al. had found that compared to healthy controls, the ACL-reconstructed subjects had greater mean CoP path velocity, ML range. The same time, they said dynamic balance performance was similar between the ACLR limb and the uninjured contralateral limb (Dauty et al., 2010).

Changes in postural control after anterior cruciate ligament injury should be considered in rehabilitation. Henriksson et al. showed significantly improved postural control in the control group when compared to the ACL reconstruction group when a backward perturbation was applied (Culvenor et al., 2016). Exercise prescriptions that stress single-limb postural control, especially techniques performed on unstable surfaces, are warranted for stage 1 of the return-to-sport phase of rehabilitation (Henriksson et al., 2001).

Ankle sprain and chronic ankle instability

Ankle sprain is very common in daily life and especially sports activities. It is known that inversion is the main mechanism in ankle sprain. It has been estimated that almost 60% of sports injuries are sprains and ligament tears (Myer et al., 2006). Chronic ankle instability (CAI) is a term used to describe certain insufficiencies that persist after an acute ankle sprain (Schneider et al., 2006).

Freeman et al. hypothesis that postural control deficiency due to damaged sensory receptors in injured ligaments after ankle sprains (Attenborough et al., 2016). However, despite the loss of sensory information from receptors in these ligaments, it may permit sensorimotor control of sufficient sensory information from other receptors (capsular, muscle-vascular, and skin) (Freeman et al., 1965).

Various studies have been conducted to investigate how postural control is affected in patients with ankle sprain (Hertel and Olmsted-Kramer, 2007; Evans et al., 2004). Evans et al. found that postural control in single leg stance was impaired, as demonstrated by increased center of pressure (COP) excursion velocity measures, on not only the limb with an acutely sprained ankle, but also on the contralateral uninjured limb (Hertel et al., 2002). Another study found that COP was more anteriorly and laterally positioned in participants with CAI compared with uninjured persons during eyes-open and eyes-closed single-legged standing (Evans et al., 2004). Having a more anterolateral COP is likely associated with the foot being more supinated, placing the ankle and subtalar joints in a closed-packed and more stable position that decreases feelings of instability in those with CAI (Evans et al., 2004).

These findings can help clinicians identify incongruous movement patterns associated with recurrent lateral ankle sprains and develop effective rehabilitation programs for correcting sensorimotor deficits following initial ankle sprain injury that may occur in CAI Pope et al. (2011).

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Chapter 27

The effects of weightlessness on human body: spatial orientation, sensory-integration and sensory-compensation

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Physical adaptation

Since the beginning of the space program, there have been great advances in our understanding of how microgravity effects (1×10^{-6} G) the brains and bodies of astronauts (Reschke et al., 2007). More recently, with the support from the National Space Biomedical Research Institute (NSBRI) and National Aeronautics and Space Administration's (NASA) Human Research programme, researchers have had the opportunity to examine the effects of weightlessness not only in space, but also on earth, using spaceflight analog studies (Palinkas et al., 1999; Koppelmans et al., 2013), and as a result, countermeasures were developed against side effects of weightlessness (Cavanagh et al., 1992; Convertino and Sandler, 1995; Manzey et al.,1995; Hargens et al., 2013).

Physiological studies showed that one of the most important factors affecting adequate adaptation to weightlessness during and after space flight missions is related to the brain's compensation capacity for the missing graviceptor signals (Buckey and Homick, 2003). The graviceptor signals from vestibular organs in the inner ear (three semi-circular canals) provide a sense of balance and orientation in three-dimensional space, while two otolith organs (the utricle and the saccule) provide information about relative motion and position in space (Buckey and Homick, 2003). In fact, even early verbal reports show that after returning to earth, shuttle astronauts report experiences of nausea, disorientation, as well as postural and locomotion difficulties (Bloomberg et al., 2015). Later studies showed that this type of incidences that are related to space motion sickness (SMS) are experienced by 44–67% of the astronauts on their first flight and up to 85% in less trained non-career astronauts (Kanas and Manzey, 2008).

Previous in-flight and parabolic flight studies reported that astronauts experienced an illusion of floor motion (Reschke et al., 1986; Lackner and Graybiel, 1981) and various other visual illusions (Oman, 2003). Moreover, pre and post-flight studies reported that astronauts experience disturbances in postural control (Bloomberg et al., 2015). These include alterations in spatial orientation during walking (Glasauer et al., 1995), reduced visual acuity (Peters et al., 2011), alterations in muscle activation (Layne et al., 1997), alterations in lower limb kinematics (McDonald et al., 1996; Bloomberg and Mulavara, 2003), head-trunk coordination (Bloomberg et al., 1997; Bloomberg and Mulavara, 2003) and sensory-motor coordination (Mulavara et al., 2010; Cohen et al., 2012). Additionally, physical problems also often occur after returning from space missions. These effects include loss of bone density (Leblanc et al., 1990, 2000a,b), decreased muscle mass (Leblanc et al., 1995, 2000a,b) and decreased red blood cells and plasma levels (Fischer et al., 1967; Udden et al., 1995). At the cellular level studies showed that cytoskeletal proteins, which are among the best-known gravi-sensitive proteins are effected the most from space flights (Pietsch et al., 2011). Other physical effects include fluid shifting from the lower to upper body (Strangman et al., 2014), cardiovascular problems (Fritsch-Yelle et al., 1994; Hughson, 2009) and changes in the immune system (Taylor et al., 1997; Sonnenfeld et al., 2003; Crucian et al., 2008). Apart from the weightlessness-related side effects of space

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flight, there is also an increased risk of cancer due to cosmic radiation in the space environment, which also limits physical adaptation (Nelson, 2009; Carpenter et al., 2010; Parihar et al., 2014).

Musculoskeletal and movement adaptations

During space-flight studies showed that there is a greater loss of muscle mass and strength in the extensor muscles (also known as anti-gravity muscles) compared to flexor muscles (Fitts et al., 2000; Trappe et al., 2009) and the loss of bone mass is evident in lower extremities (LeBlanc et al., 2007). These findings show that the most weight-bearing bones and muscles are effected during a space flight mission.

Studies that examined bone related changes showed that there are time dependent changes in the metabolic cycle of the bone remodeling. The most consistent result from these studies was found to be the negative calcium balance (Smith et al., 2005; Smith et al., 2012) that is caused by the reduction in the intestinal absorption of calcium and increase in the urinary calcium. Imbalance between bone-forming osteoblasts and bone-resorbing osteoclast was also reported (LeBlanc et al., 2007). Furthermore, studies showed that the most affected joints from space flight were hip and spine joints, i.e. pelvic bones, lumbar vertebrae, trochanter and the femoral neck (Grigoriev et al., 1998; LeBlanc et al., 2000). On average, the loss of bone mineral density (BMD) was reported as 1% per month at the spine and femoral neck and 1.5% per month at the trochanter. BMD of the calcaneus (heel bone) was reported to decrease with the length of flight (LeBlanc et al., 2000) but this loss was smaller than the loss in spine. The most sensitive joint was found to be the hip joint as it is in postmenopausal osteoporosis (Lang et al., 2004). Studies that made volumetric measurements of the BMD showed changes in the trabecular compartments of the bone, which was approximately 2.2–2.7% per month. While these detrimental effects were observed in lower extremity, measurements in upper-extremity, e.g. wrist joint, resulted no changes in BMD (LeBlanc et al., 2007). After space flight follow-up studies showed that BMD return to its preflight values after one year, but trabecular bone and integral volumetric bone density do not fully recover. In addition, femur bone has been found to be larger in size compared to pre-flight which suggests that there are irreversible changes occur in bone the tissue (Lang et al., 2017).

Interventions to prevent such detrimental effects include exercise programs with resistive and aerobic loading along with nutritional and pharmacological approaches and physical interventions. Impulsive mechanical stimulation, which mimic the heel strike during normal walking, was used to stimulate femur and calcaneus (Goodship et al., 1998). The effects of different magnitude and frequency of mechanical stimulations have been shown for bone mass loss; a low magnitude and high frequency mechanical load, like during postural control, has been suggested as a way to counteract the bone mass loss in microgravity (see Nagaraja and Jo, 2014 for review).

Severe loss of muscle mass and strength in trunk and lower limbs have also been documented in space missions despite the exercise countermeasures. Studies investigated the effects of short-duration missions that are between 8 and 16 days have reported atrophy in hamstrings, quadriceps, soleus and gastrocnemius, anterior calf muscles and intrinsic back muscles. In long-duration missions more extensive losses of muscle mass in the same group of muscles have been found (Lang et al., 2017). There has been a limited number of biopsy studies revealed the changes at the level of myofibers. Edgerton et al. (1995) examined vastus lateralis by biopsy and found that fast twitching type IIb and IIa fibers showed more atrophy than the slow twitching type I fiber (IIb > IIa > I) and Widrick et al. (1999) showed consistent findings in soleus muscle. Also, fibers in soleus muscle was also found to be more affected than the gastrocnemius both in rats and in humans (Fitts et al., 2000). A recent study by Trappe et al. confirmed these findings and reported that after 6 months space mission crew showed decrease in culf muscle volume with greater atrophy of soleus (−15%) compared with gastrocnemius (−10%) and decrease in peak power of culf muscles (32%) (Trappe et al., 2009). Study also showed the redistribution of fibers from fast to slow twitching in the gastrocnemius and soleus muscles. It should be noted that these changes took place even though the crew members applied an exercise program that contained running, cycling and resistance exercise during 6-month space missions.

In addition, there has been studies examining explosive power of the lower limbs. Explosive power decreased 60–80%, which might relate to atrophy of fast twitching type IIb and IIa fibers (Antonutto et al., 1995). Maximum explosive power in leg-push reduced 67% and recovered later than maximal cycling power, which was also reduced in power (Antonutto et al., 1999). In general, atrophy is accompanied by reduced strength and increased fatigue or muscle soreness. However, magnitude of the loss of strength was much more than the loss of muscle mass indicating a different motor control mechanism (Lang et al., 2017). LeBlanc suggested that there seems to be a new steady-state, or baseline, condition for muscle mass, which occurs after 4 months of microgravity exposure (LeBlanc et al., 2000). Given the effect of long duration flight on bone and muscle, it is not hard to expect changes in gait and feeling of 'heavy limbs' reported by astronauts (Ross et al., 1986). Adaptation in kinematic properties of head-trunk coordination during walking showed decrease in magnitude of pitch head movements as astronauts tried to restrict the head movement after space mission (Bloomberg and Mulavara, 2003). Similar adaptation of head-trunk movements are also observed in patients suffering from vestibular deficits (Borel et al., 2002) and during the development of head stabilization in infancy (Assaiante, 1998). This adaptation has been shown to be related to changes in gaze stabilization strategies (McDonald et al., 1996; Bloomberg et al., 1997).

Spatial orientation

Spatial orientation is one of the most important resources available to the balance system. This allows body orientation with respect to gravity and the surrounding environment during resting and motion. It is known that healthy individual can identify gravitational verticality within 0.5° sensitivity (Horak, 2006), and that multiple regions of the brain are responsible for the perception of verticality (Karnath et al., 2000). On earth, the vestibular system provides information about the motion of the head and its position in relation to gravity, but during weightless, the verticality information (up and down cues) processed by the inner ear vestibular system cannot fully function; therefore, astronauts have to rely on other senses. It was reported that while during training and the flight missions, crew members can easily adapt to weightless environments, but later, re-adaptation to earth's gravity involves many changes in cognitive and brain processes (Buckey and Homick, 2003). Understanding these cognitive processes and the duration of re-adaptation is not only important for earth-lauched missions, but will also be important for future mars-based missions, where astronauts will have to adapt Mars gravity (0.38-G) after long duration space flights.

One of the most important brain regions for spatial orientation is the vestibular cortex (Zu Eulenburg et al., 2012). The vestibular cortex is thought to be responsible for the perception of verticality (Brandt et al., 1994; Brandt and Dieterich, 1999; Baier et al., 2012). However, the factors that thought to be involved in perception of vertically is more complicated than it seems such that individuals with lesions to the vestibular cortex (intraparietal sulcus and parieto-insular vestibular cortex) do not necessarily suffer from a tilted posture or a loss of lateral balance (Karnath et al., 2000). Also there is evidence from Spacelab-D1 (Young et al., 1986) and Spacelab IML-1 missions (Benson et al., 1997) which showed that in the absence of graviceptor signals, astronauts perceived only rotation but not tilt. This combined evidence suggests that there is more than one internal representation of verticality in the brain, and that different verticality centers of the brain may compensate for one another in the case of disruption in one particular area.

The Somatosensory system, the second most important brain system for perception of verticality, may also serve as a compensatory modulator for vestibular graviceptor signals. Historically, the somatosensory cortex was believed to be an "association" area, associating motor cortex and visual cortex, and responsible from attention and spatial awareness (Berlucchi and Aglioti, 1997). Accumulated evidence in recent years shows that this area for sensory-motor integration is crucial for cognitive plans, reaching and grasping movements, as well as eye movements (Husain and Nachev, 2007). It was demonstrated that lesions to this area also produce optic ataxia (Karnath, and Perenin, 2005), and hemi-neglect (Vallar, 1998), in which patients' stimulus localization is impaired (Rossetti et al., 2005). The Somatosensory system receives information from muscles, skin, and joints, processes this proprioceptive information, and thus can compensate for an impaired vestibular system (Barra et al., 2010). For example, individuals susceptible to mal de debarquement symptoms a sickness that causes illusion of movement after traveling by sea, are known to depend more heavily on somatosensory cues (Nachum et al., 2004). Few reports also showed that after long-duration space missions astronauts also experience similar symptoms (Clément, 2005; Lackner and DiZio, 2006).

The brain appears to integrate visual, somatosensory and vestibular representation in order to create a sense of verticality (Barra et al., 2010). The working hypothesis is that each of these three sensory systems provides both unique and redundant information for the perception of verticality and postural control. Space mission experiments with animals exposed to microgravity exposure showed structural brain changes, particularly in the somatosensory cortex and cerebellum (Holstein et al., 1999; Krasnov, 1994). However, there is little information on how somatosensory processing affects sensory compensation, studies are needed to gain a clearer understanding on the influence of somatosensory system on perception of verticality (see for a discussion Bloomberg et al., 2015).

Sensory-compensation: sensory integration and sensory weighting

An important hypothesis that describes how the particular function of a brain region is compensated by other brain regions after an impairment is called the "*sensory compensation hypothesis*" (Larson and Pranke, 1999; Clement and Reschke, 2008). According to this hypothesis, people rely on other sensory modalities when the information from one modality is disrupted or missing. In fact, it has long been known that astronauts increase their reliance on visual cues, in the absence of vestibular information (Young et al., 1986; Clement et al., 1984). This suggest that in order to adapt to weightlessness, astronauts have to re-interpret the visual and proprioceptive information (Paloski et al., 1992; Paloski et al., 1994; Reschke et al., 1998).

At the heart of the sensory compensation hypothesis lie two core concepts: *sensory integration* and *sensory weighting*. Sensory integration, also called multisensory integration, refers to the integration of neural information from different sensory modalities, such as vestibular and somatosensory modalities. The *sensory integration* view is relatively new compared to the concept of localized or unimodal information processing. During the early 20th century, the general view among neuroscientists was that cortical regions were highly functionally specialized, and could not be affected by other sensory modalities (for a review, see Mesulam, 2000). From the mid 1960s, Hubel and Wiesel (1965) contributed not only to the development of the ideas of orientation columns in the primary visual cortex, but they also revealed extensive cortico-cortical connections between different layers of the cortex, and showed that these connections are hierarchically organized. Before this surprising finding, the field had been dominated by the localization perspective, and little was known about the cortico-cortical connectivity. By the 1980s and 1990s, with the view of distributed representation on the one hand (Hinton et al., 1986) and neuroanatomical findings on the other (Stein and Meredith, 1993), multisensory integration became widely accepted, but the knowledge of the exact neural mechanisms involved was still underdeveloped. More recently, a growing body of evidence shows that even primary sensory areas of the brain, such as the primary visual and somatosensory cortical regions, can be affected by information from other sensory modalities (Stein and Meredith, 1993; Calvert et al., 2004; Stein and Stanford, 2008; Stein, 2012).

An advantage of multisensory integration is that when the sensory regions are activated by a particular event, integration of sensory cue information from different modalities could improve detection and identification the event, possibly leading to an increase in the speed of motor responses (see, Stein, 2012 for a review). The seminal work of Stein (2012) described this and other functional interactions in the superior colliculus, outlining a number of empirical principles that were to guide multisensory research for over two decades, (see for details James and Stevenson; 2012; Beauchamp et al., 2004; Driver and Noesselt, 2008; Stein and Meredith, 1993; Stein and Stanford, 2008).

Although these novel findings on multisensory processing is highly relevant to many neuroscientists, the underlying neuro-computational processes are still not well understood (Trommershauser et al., 2011). One candidate model that could explain multisensory information processing is called Bayesian processing (Körding and Wolpert, 2006). Bayesian views of information integration are based on combining cues and weighting their reliability (Körding and Wolpert, 2006). Bayesian models of sensory integration were tested in humans in different psychophysical paradigms (Ernst and Banks, 2002; van Beers et al., 2002; Alais and Burr, 2004), showing that humans usually perform as near-optimal Bayesian observers.

The other core concept of sensory compensation is related to sensory weighting which refers to the capacity of the nervous system to attribute different weights to the available sensory information (external and internal), from different modalities. During sensory weighting, sensory cues providing more accurate information are prioritized while performing a task, and information from others modalities are suppressed. This is a crucial neural process in sensory compensation, and during a spaceflight mission, it is possible that astronauts might experience difficulties in prioritizing sensory weights from different modalities.

Sensory-compensation in weightlessness

One of the most important aspects of postural stability and balance is the ability to control the body's center of mass (COM) relative to the base of support: the feet. Here, the standing equilibrium is defined as the area in which one can move their COM at their base of support and maintain equilibrium. It is thought that the brain has an internal representation of this cone of stability, and this working model is used in reactive and in anticipatory strategies to maintain equilibrium (Horak, 2006). It is a combination of both physical and psychological constraints that ultimately determine an individual's cone of stability. Correct estimation of COM position relies on the integration of information from three separate sensory modalities: the visual, vestibular, and somatosensory modalities (see Fig. 27.1).

Over the years, a substantial amount of empirical and theoretical work on sensory weighting during postural control has been accumulated (Carver et al., 2005, 2006), and multiple measurement techniques were used for postural control. These include the rail test performed after the Apollo 16 (Homick et al., 1977) and Skylab missions (Homick and Reschke, 1977), as well as the tilting room experiments that test the relative importance of visual, somatosensory and vestibular senses on postural control (Von Baumgarten, 1986). Moreover, dynamic posture platforms (Kenyon and Young, 1986), Functional mobility test (FMT) (Mulavara et al., 2010) and clinical

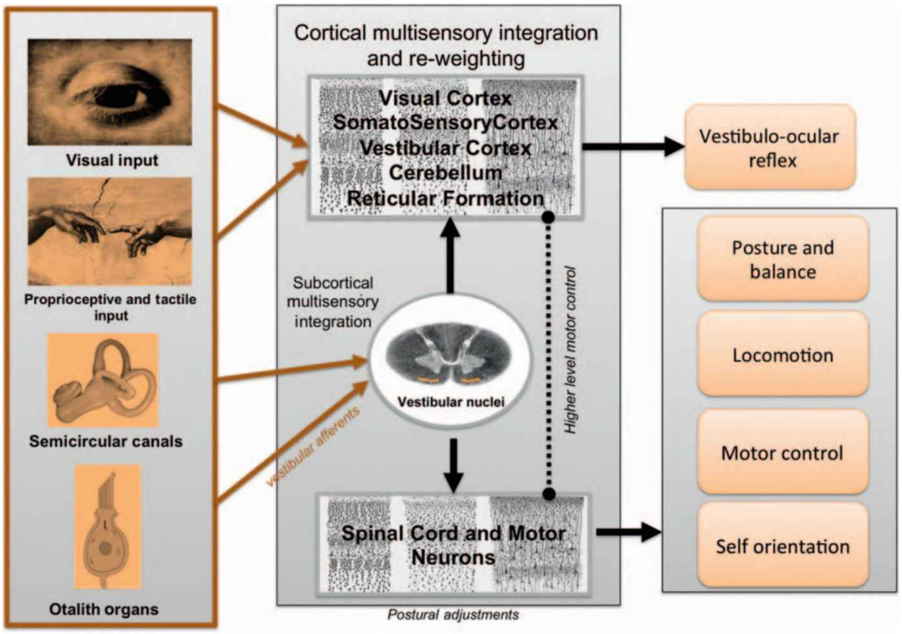

FIGURE 27.1 Schematic representation of multisensory integration for postural control. The brain uses information from variety of sources to synthesize a sense of body orientation, balance and movement. The integrative centers can adapt to a variety of unusual sensory situations.

posturography systems (Neurocom International) are commonly used tools to assess the magnitude of postural instabilities of astronauts returning from space shuttle missions (Paloski et al., 1993). Measurement techniques, such as the sensory organization test (SOT), are commonly used with healthy non-astronauts to test the effects of six different sensory conditions (Honrubia et al., 1997). The SOT measures the amount of visual, somatosensory and vestibular input, and systematically manipulates these modalities in order to measure the contribution of each sense in postural control (Honrubia et al., 1997). Horak (2006) and Peterka (2002) concluded that the relative weight of sensory cue information of is 70% somatosensory, 10% vision and 20% vestibular. Early work and recent studies on multisensory integration and postural control concluded that the weighting process in the nervous system is more sensitive than previously thought (e.g., Nashner et al., 1982; Woollacott et al., 1986). For example, Oie et al. (2002) showed that sensory reweighting occurs with amplitude of postural sway changes as small as 2 mm. The results of this study imply that the weighting of sensory information might even occur during routine motions in order to generate new estimates of the COM for upright stance control. However, as mentioned earlier, during a space-flight mission, diminished visual inputs due to optical problems (Mader et al., 2013) that astronauts' experience may limit their ability to re-weight sensory inputs from other modalities in response to changing environmental inputs. In such a case, astronauts may not be able to rely on the compensatory modalities to the same extent as healthy individuals due to the possible unreliability of the compensatory mechanism (Mader et al., 2011). A healthy individual may rely less on somatosensory inputs and more on vestibular inputs when on an uneven surface, correspondingly astronauts on space flights rely less on vestibular input and more on somatosensory and visual inputs. In fact, research showed that astronauts experience the greatest difficulty when relying solely on the vestibular information (Lawson et al., 2016).

Decrements in postural stability with eyes closed are well documented from Skylab missions, and were observed to persist for up to 1–2 weeks' post-flight (Homick et al., 1977). Earlier studies reported that in space, the body's COM is forward tilted (25°), shoulders up and arms float (Thornton, 1978), and astronauts show greater head-down orientation (Tafforin and Lambin, 1993). Tafforin and Lambin (1993) reported that astronauts in space show more frequent head and body movements in yaw direction compared to on the ground. In addition, Clement et al. (1984) reported an increase in anterior tibilialis muscle tone, perhaps as a result of a change in motor strategy. It is possible that the brain develops a new internal representation of the environment and object locations in microgravity based on a new internal model of gravity that is shifted more anteriorly (Clément et al., 2001). Moreover, Paloski and Colleagues (1992, 2004) showed that crew members performed similar to vestibular deficient patients on SOT task (Speers et al.,1998).

Finally, recent studies suggest that astronauts may be able to overcome some of the somato-sensory cortex related functional loss with appropriate physical exercise (Roller et al., 2001; Koppelmans et al., 2015). Physical exercise has been shown to be effective in rehabilitating patients with balance (Lord et al., 1995), motor coordination (Roller et al., 2001; Seidler, 2004) and locomotion problems (see for a review, Green and Bavelier, 2008). It possible that exercise interventions might ameliorate negative side effects of weightlessness on the human balance system (Loehr et al., 2015; Petersen et al., 2016).

Sensory compensation and cognitive functions

In the previous section, it was concluded that in order to adapt new environments, the nervous system has to integrate or weight certain groups of sensory signals from a variety of modalities. The brain performs this adaptation by changing the functional connectivity or its anatomical plasticity. As mentioned earlier, the balance system uses various sensory signals from different modalities which are converted into appropriate motor responses in the absence of fully functioning vestibular system. In normal healthy individuals it was showed that increasing the difficulty of the postural task by temporarily impairing sensory inputs needed additional cognitive resources (Teasdale and Simoneau, 2001). In normal healthy individuals, this increased cognitive demand may be adequate to prevent effective loss of balance, but during a space mission, the cognitive resources may be occupied by operational task requirements, and therefore dual task requirements could have negative influences on task success (Seidler et al., 2015). Therefore, it is crucial to understand the contribution of cognitive resources to sensory compensation during a spaceflight.

Previous studies showed that dual tasking during cognitive and motor behaviors is significantly affected in microgravity environment (Manzey et al., 1993; Manzey et al., 1995; Manzey et al., 1998; Bock et al., 2010). In addition, in Manzey et al. (1998) it was found that task interference was independent of the difficulty of the memory search task, suggesting that the critical resources affected were probably not those related to memory, but rather, those pertinent to motor programming. However not all studies showed that cognitive resources are negatively affected by space flight (Fowler et al., 2000; Strangman et al., 2014; Koppelmans et al., 2015). In a recent meta-analysis of 32 studies investigating the adverse neurocognitive effects of short and long term spaceflight, none were able to provide strong statistical support for spaceflight-induced cognitive deficits (Strangman et al., 2014).

Several studies also showed changes in human brain structure and function following a spaceflight (Koppelmans et al., 2016; Cassady et al., 2016; Pechenkova et al., 2019) and Head-down tilt bed rest (Liao et al., 2012; Li et al., 2015; Roberts et al., 2015; Koppelmans et al., 2017b), specifically in the frontal, motor and somatosensory regions (Koppelmans et al., 2017b). For example, Koppelmans and colleagues (2016) evaluated T2-weighted MRI scans from 27 astronauts, and demonstrated gray matter decreases in the temporal and frontal regions. They also found gray matter increases in the medial primary somatosensory and motor cortical areas. Supporting this finding, Koppelmans and colleagues (2017b) in a Head-down tilt bed rest (HDBR) analog study showed gray matter increases in posterior parietal regions, possibly associated with balance and locomotor performance. However, another study by Koppelmans and colleagues (2017a) reported that these changes mostly effect the intracranial fluid redistribution and they found no white matter changes during a 70-day head-down tilt bed rest study.

Finally, a recent Head-down tilt bed rest (HDBR) functional MRI study, of which the protocol has been published previously (Koppelmans et al., 2013), showed increased activation during dual task condition compared to a single task condition during a space flight analog study (Yuan et al., 2016). More specifically Yuan and colleagues (2016) showed significant changes in a widely distributed network that includes the frontal, parietal, cingulate, temporal, and occipital cortices, possibly indicating a greater need for cognitive resources for dual task execution during bed rest. Future studies will highlight the underlying causes of these neuroplasticity changes.

Conclusion

In this chapter, weightlessness and its potential effects on multisensory integration and sensory weighting were discussed. The definitive evidence on these issues were limited to space flight studies and ground-based analog studies with small sample sizes (Strangman et al., 2014). However, it is clear that sensory integration is essential for accurate perception and behavioral performance, yet the reliability of the sensory signals during a space flight might vary across modalities, a potentially important factor for sensory re-weighting (Paloski et al., 1992, 1994; Reschke et al., 1998). Rigorous research is needed to understand the issues of how weightlessness affects different sensory modalities, and how cognitive resources can compensate sensory disturbances during spaceflight.

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Part 8

Locomotion

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Chapter 28

Evolution of bipedalism

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Introduction

Bipedalism is the ability to stand and walk entirely on two feet. The bipedal gait had evolved 4 million years ago and is characteristic to modern humans (Hunt, 2015). Efficient locomotion and unloaded and free hands are the main advantages of bipedalism. As our early ancestors had stood up and walked, many morphological changes began to emerge. The evolutionary factors that produced these changes have been the subject of several theories. The reason why bipedalism has become a form of locomotion is explained by several hypotheses. The most popular hypothesis is bioenergetics/thermoregulation model. Bipedalism is energy efficient at slower speeds over longer periods of time (Wheeler, 1991; Foley, 1998; Rice and Moloney, 2016). Bipedal human walking is highly energy efficient as the distance between main center of mass and the segmental center of mass (thigh, leg etc.) is relatively shorter, therefore the movement against the torque created by gravitational forces requires less amount of energy compared to those of quadrupeds. Moreover, all segmental movements can basically be considered as pendular motions, where the potential energy is converted to kinetic energy.

Walking energetics and biomechanics for adult chimpanzees and humans were analyzed to investigate the hypothesis that bipedalism reduced the energy cost of walking compared to our ape-like ancestors (Sockol et al., 2007). Researchers found that human walking is 75% less costly than both quadrupedal and bipedal walking in chimpanzees. Variations in cost between bipedal and quadrupedal walking, as well as between chimpanzees and humans, are well explained by biomechanical differences in anatomy and gait, with the decreased cost of human walking attributable to our more extended hip and longer hindlimbs. It is concluded that analyzes of bipedal walking in chimpanzees indicate that bipedalism in early, ape-like hominins could indeed have been less costly than quadrupedal knuckle-walking.

Bipedalism also makes it easier to regulate body temperature by reducing direct solar radiation exposure (Wheeler, 1991). According to "social display hypothesis" bipedalism increases social status, access to food or mates. Walking erect also improves communication. Infant-carriage as well as food-carriage hypotheses identified the need for free hands to carry items over long distances. Free hands were more advantageous in terms of tool manufacturing and their efficient use. Bipedalism also allowed our ancestors to look over large objects and see potential predators and also for possible food sources.

Evolving ideas and theories

Several hypotheses proposed for evolution of bipedalism (Hunt, 2015): Darwin hypothesized that two of the most striking human characteristics, large brains and upright locomotion, were linked in a "tool-use hypothesis." This first true evolutionary hypothesis for the origin of bipedalism is now disproven by the fossil record: human-sized brains evolved only in the last million years, whereas the first stone tools appeared over a million years earlier. The "social display hypothesis" was that bipedalism evolved because it increased the apparent size of the individual, thereby increasing social status and access to food or mates, or intimidating predators.

Some theories linked bipedalism as freeing the hands to carry either infants or food and items. The "infant-carriage hypothesis" recognized that brain expansion came late in human evolution, and instead identified the need for females to support infants with their arms thus selecting bipedal locomotion. The "food-carriage hypothesis," the idea that bipedalism freed the hands to carry food to mates or other relatives or group members, emerged in mid-century and gained momentum during the 1970s and 1980s. The "locomotor efficiency hypothesis" considers the efficiency of bipedalism over quadrupedalism as

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critical. The "thermal radiation avoidance hypothesis" suggested that bipedalism evolved to reduce exposure to solar radiation.

Other hypotheses speculated that bipedalism freed the hands for gathering food. The "seed eating hypothesis" proposed that early hominins stood erect to gather grass seeds, and that the small size of seeds demanded a bipedal, alternate-hand plucking action to achieve a reasonable rate of ingestion. The "small-object feeding hypothesis" substitutes small-diameter fruits in short trees and bushes for grass seeds. Trees are not easily pulled over. The "postural feeding hypothesis" adds an arboreal component to the small-object feeding hypothesis.

Evolution of bipedalism

Facultative and habitual bipedalism are two different forms of standing and walking on two legs. Facultative bipedalism is when an animal that usually locomotes on more than two legs assumes a bipedal position on a temporary basis in order to perform a specific action. Quadrupeds, such as African antelopes or chimpanzees may assume a bipedal position for feeding or defensive purposes. Facultative bipedalism is an early form of human bipedalism probably used from 6 to 1.8 million years ago that likely was accomplished with the knees bent and without a full stride. Habitual bipedalism is when an animal's natural form of locomotion is on two legs. Habitual bipedalism is the modern form of bipedalism that first appeared in fossil record 1.8 million years ago (Homo Erectus times) and that is accomplished with straight legs and full strides (Rice and Moloney, 2016).

An evolutionary step that followed bipedalism is larger and more complex brains, allowing the development of problem-solving abilities and behavioral changes (Rice and Moloney, 2016). Increased brain size and ability to walk upright were classified as two key evolutionary features of humans. In papers describing Uner Tan Syndrome, reverse evolution was discussed as the syndrome presents itself with a regression from bipedalism to habitual quadrupedalism (the gait of our early ancestors), impaired intelligence, ataxia and cerebro-vermial hypoplasia (Tan, 2010). Uner Tan Syndrome was first described in 2005 among 14 members of four families in Turkey (Tan, 2007). Cases were normal at birth, crawled normally, walked upright but then regressed to habitual quadrupedalism. From a paleo-neurological point of view Uner Tan syndrome may be related to the theory of human backward evolution.

Morphological adaptations that are crucial to support and enable this new form of locomotion include: a more inferiorly placed foramen magnum, larger femoral heads, increased femoral neck length, condyles of the femur elongated in the anterior-posterior directions, the knee positioned in slight valgus due to bicondylar angle, shorter big toe, and a higher foot arch. The anatomical adaptations that would make bipedalism more efficient are presented in Table 28.1.

Skull

For upright standing and walking, the skull needed to be attached to the spinal column in a more balanced position. In quadrupeds, the spinal column runs parallel to the ground so that foramen magnum is more dorsally placed. However, in bipeds, spinal column runs perpendicular to the mandible and the ground, therefore foramen magnum was gradually located more to the center of the base of the cranium to improve balance (Fig. 28.1). By the help of this transformation weight of the cranium is transferred posteriorly to the spine enabling brain development (Hunt, 2015).

Arms and legs

Modern humans' arms are shorter than the legs. The main difference between modern humans' arms and their early ancestors is that the arms are no longer needed for locomotion and used only for carrying and grasping objects. The scapula has changed its position from lateral to posterior and the clavicle was bent forward to allow greater mobility in the forelimbs.

Spine

Bipedalism requires spinal balance (i.e., the trunk is maintained over the top of the femoral heads); this is reflected in normal spinal curvature. Our early ancestors had a single curved spine however evolution of upright posture and bipedal gait imposed specific demands on the spinal column. The arched shaped spine is not efficient for bipedal walking. As an adaptation to provide better balance and weight distribution for bipedalism, the spinal geometry changed its shape from an arch to the shape of a double "s" with four natural curves (Fig. 28.2). Natural curves are cervical and lumbar lordosis together with congenitally existing thoracic and sacral kyphosis. This change allows us to maintain balance in upright position.

This transformation offers greater efficiency as it requires less energy to maintain spine in upright position. Natural curves also enable to reduce ground reaction forces (GRF) transmitted to proximal regions during walking. For every step taken, the whole body weight is supported by one of the limbs during single leg stance. The ground produces an opposite reaction to the weight transferred down with every step. Natural curves prevent

TABLE 28.1 The anatomical features indicative of bipedalism.

Skull	• Foramen magnum was gradually located more inferiorly to the center of the base of the cranium to improve balance (Fig. 28.1) • Humans have the nuchal ligament that reduces the need for muscle action during running • The semicircular canals are re-shaped to maintain balance and stabilize visual field during locomotion
Arms and legs	• Longer legs than arms • The scapula changed from a lateral position to a dorsal position and the clavicle was bent forward to allow for greater mobility in the forelimbs • Less curved phalangeal shafts • Modern humans are capable of a more precise grip than early ancestors • Flat surface of the medial cuneiform
Spine	• Humans exhibit a combination of thoracic kyphosis and lumbar lordosis to maintain spinal balance
Sacrum	• The sacrum along with the spine was pulled backward, leaving the anterior superior iliac spine in front of the hip joint, retaining the lever arm for the muscles of the anterior thigh • Broad sacroiliac joint surface indicative of a pronounced lumbar curvature
Pelvis	• The pelvis was re-shaped as the spine was rotated to a vertical rather than horizontal position (Fig. 28.2) • A more posterior orientation of the anterior portion of the iliac blade
Hip	• Humans have a stronger femur • The femoral head is relatively larger compared with that of early ancestors • Femoral neck length is increased and condyles of the femur became slightly larger and elongated in an anterior-posterior direction • Laterally shifted and more flared iliac ala • The bicondylar angle formed between the knee and hip, allows humans to maintain balance while walking upright (Fig. 28.3) • Gluteus medius and minimus evolved to serve as abductor muscles to help stabilize the body in coronal plane
Knee	• A bicondylar angle or the valgus knee due to enlarged and elongated femoral condyles
Foot and ankle	• The human feet have adapted to support a bipedal body structure • The calcaneus is broadened, thus reducing pressure during heel strike on tissue covering it • A higher arch on the foot • Human hallux lies parallel to the other toes and lateral movement is severely limited • The presence of a shortened big toe • Humans have smaller toes than their bipedal ancestors

the reactive force produced by the ground at every step we take that would otherwise affect the entire skeleton.

Spinal curves contribute to the structural stability of the spine. Newborn infants have a spine with primary "C" shaped curve. Cervical and lumbar curves develop as secondary curves with growth and maturity. Cervical lordosis allows the infant to visually access his environment supporting motor development, such as reaching, grasping objects and intentional crawling. Lumbar lordosis which forms between ages of 1–10 years is essential to human upright posture. The development of this lumbar curve helps the child to gain unsupported sitting and eventually standing, walking and running.

The lumbar lordosis is crucial in allowing us to maintain upright balance and walk. Lumbar curve pulls upper body back over the pelvis and positions the body inward over pelvis. This helps to keep the center of gravity directly over the feet and therefore allows us to maintain balance. The cervical curve supports the weight of the skull. However, the sacral curve does not support much body weight.

Sacrum

Articulating with L5, sacrum is the end of the spine. For bipedal walking along with the spine sacrum was pulled backward so that anterior iliac spine stayed in front of the hip joint. Repositioning of the anterior iliac spine enabled mechanical advantage in terms of lever arms for the anterior thigh muscles (Hunt, 2015).

Sacrum articulates with pelvis via sacroiliac joints. Sacroiliac joint surfaces are larger in human beings compared to early ancestors due to differences in weight transmission pattern from spine to pelvis and lower extremities in bipedal gait.

Sacrum is usually defined as an undeveloped tail. In animals length of the tail depends on the need of balance.

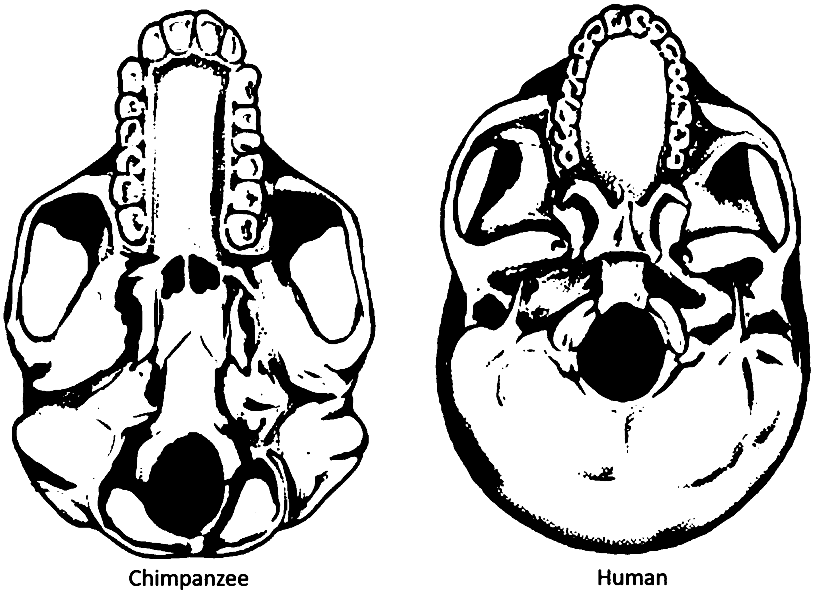

FIGURE 28.1 Foramen magnum was gradually located more inferiorly to the center of the base of the cranium to improve balance.

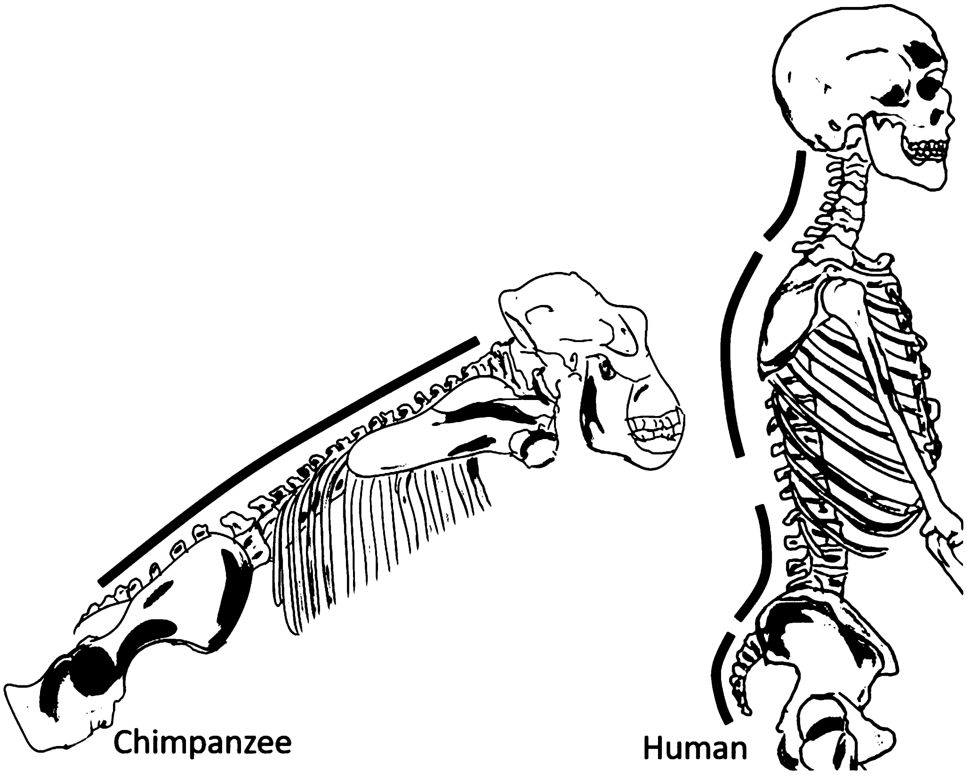

FIGURE 28.2 The spinal geometry changed its shape from a single arch to the shape of a double "s" with four natural curves.

Human beings no longer need a tail as they are sufficiently balanced on two feet.

Pelvis

The modern human pelvis is much shorter and wider than our early ancestors forming an efficient supportive system for bipedal locomotion providing stability and the ability to support greater amount of weight on two legs. Early ancestors have long flat pelvis whereas human pelvis adjusted for bipedal walking by changing angle and shape like a bowl to support organs and lower center of gravity for better balance on two legs (Fig. 28.3). The internal organs of bipeds hang less from the spine and rest in a

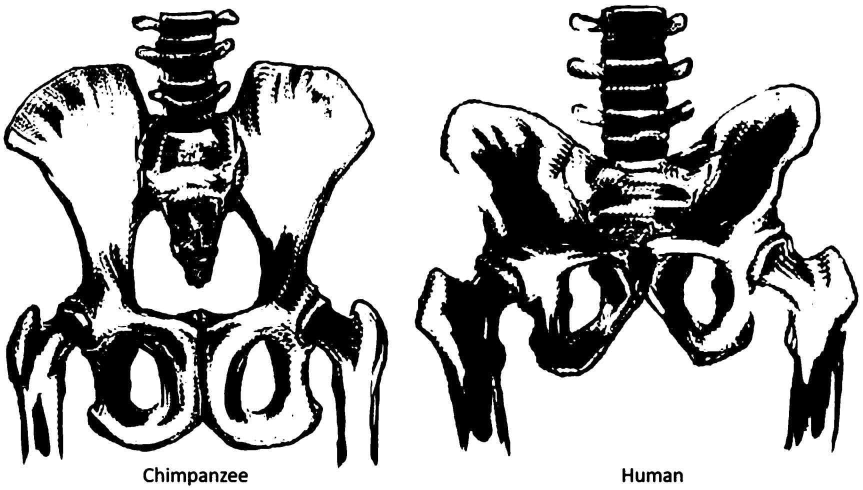

FIGURE 28.3 Comparison of human pelvis with early ancestors. The pelvis was reshaped as the spine was rotated to a vertical rather than Horizontal position.

more bowl-shaped than blade-shaped pelvis (Hunt, 2015). Larger pelvic outlet in human beings allowed enough space for large brained infants to pass through the birth canal.

Hip abductor muscles (gluteus medius and gluteus minimus) originate from the dorsal side of the ilium and insert on the greater trochanter of the femur. They evolved to serve as abductor muscles to help stabilize the body in coronal plane during bipedal locomotion. During evolution of bipedal gait, increased demand on hip abductor muscles re-shaped human pelvis and re-positioned the hip abductors to support upright posture (Warrener, 2017).

In humans, the curved iliac blades provide stability and support for the weight of standing upright and walking. Quadrupeds had different pelvis structures allowing them to support strong muscles for climbing. The most remarkable difference is their long narrow iliac blades. These extend along each side of the sacrum in line with spine. Sacrum of quadrupeds is straight and narrow. In bipeds iliac blades have changed to be able to support all the weight of the upper body and also in the case of females to give birth to babies with big skulls. The pelvic structure has permitted the development of strong muscles which allow humans the unique ability to walk on two legs during long periods of time without spending too much energy.

The re-orientation of the ilium required two other changes which were not direct causes of bipedalism. When the ilium rotated to support a greater amount of weight another problem arose. This was the need to hold muscles and vital organs together. For this reason sacrum, which separates the ilium at the back of the pelvis has grown wider and the ilium has changed its shape.

Body weight is transferred to legs via acetabulum. In the past, this connection was made further up on the ilium but as the femur needed to be connected in such a way that it could support the weight of the torso and at the same time move, it needed to be lowered. Another important change was the flattening of the ischium that provided the ability to be able to sit.

Hip

In bipeds, the hips support and balance the weight of the torso during locomotion. Modern human hip joint is larger than early ancestors as well as shorter and broader to support more body weight and to cope better with the stresses produced while walking. Because all body weight is borne the legs reciprocally, the head of the femur, or hip joint, is large compared with that of early ancestors, to accommodate the additional stress (Hunt, 2015). A femoral head with a larger diameter is able to absorb more stress. Another adaptation to counteract the increased stress on the hip joint is the longer femoral neck, which increases the mechanical advantage of the lesser gluteal muscles by lengthening their lever arm.

Acetabulum needed to be lowered for improved support to the weight of the torso during bipedal locomotion. When early hominids started to walk upright there was a need to place the vertebral column closer to the hip joints in order to provide a stable base for the trunk when in motion. When weight of the trunk is placed above the hip joints and transferred to two legs to absorb the great amount of stress femoral head and accordingly acetabulum got larger. This change in the shape brought the spine closer to the hip joint providing a stable base for supporting the trunk while walking upright. Placement of the spine closer to the hip joint allows humans to invest less muscular effort for balancing.

When early hominids started to stand and walk there was a great amount of stress on their hip joints and femur.

However, human beings have a longer femur angled to the midline allowing better support of the weight and to walk more efficiency (Tattersall and Schwartz, 2001).

Bipedalism created the need to be balanced while standing (Skoyles, 2006). To do so, the center of gravity needs to be sustained over each leg reciprocally during walking. The femur angles inwards so that the knee joints come closer together placing the feet directly underneath the center of gravity. The entire weight of the torso is transferred through the legs and to the feet during bipedal standing and walking. Therefore, the femur in bipeds is one of the most critical links between the pelvis, vertebral column, and lower legs. The femur is also the distal attachment point for the gluteal muscles that provide the propulsive force for locomotion (Hogervorst et al., 2009).

The bicondylar angle (8°−11° in humans) is the angle between an axis through the shaft of the femur and a line perpendicular to the infracondylar plane and is often used as a marker of bipedalism (Fig. 28.4). Shefelbine et al applied loading conditions to the model to simulate loading during single leg stance phase of bipedal gait (Shefelbine et al., 2002). The stresses in the epiphysis of the distal femur that result from bipedal loading conditions promote growth and ossification more on the medial side than on the lateral side of the femur, forming the bicondylar angle. This model explains the presence of the bicondylar angle in human bipedalism and also the ontogenetic development of the bicondylar angle in typically growing children. The mechanobiological relationship between endochondral ossification and mechanical loading provides valuable insight into bone development and morphology.

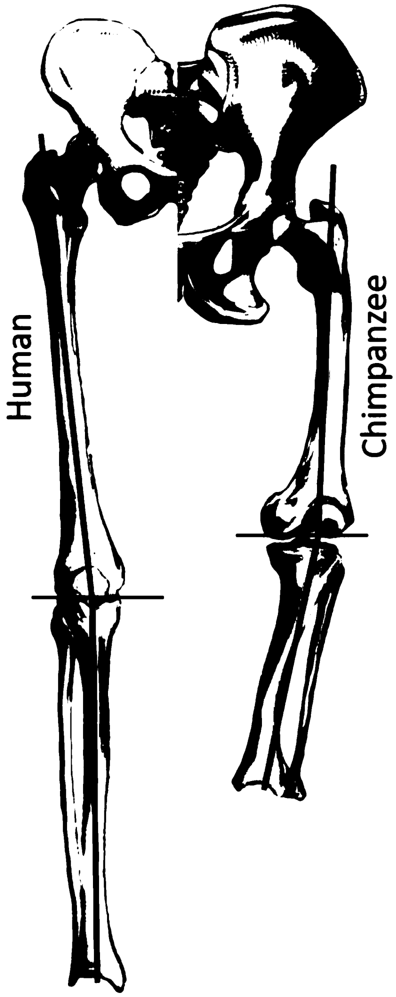

FIGURE 28.4 Bicondylar angle as a marker of bipedality.

When a child is born, the axis of the shaft is perpendicular to the metaphyseal growth plate. When a 1-year-old child first starts to walk, the medial side of the distal metaphysis grows faster than the lateral side, resulting in the bicondylar angle (Fig. 28.4). The angle reaches a stable value of 8°−10° by the age of 8 years. In bedridden children, children with neuromuscular disorders, and paraplegic children who do not walk during the early stages of childhood development, the bicondylar angle does not form. The formation of the bicondylar angle is a skeletal response to the changes in locomotor activity.

The knee

During bipedal walking, the feet are placed close to the centerline of the body to reduce sway. Tibia creates a platform for femur, which is perpendicular to the ground to rest during stance phase. Femurs angle inward from their lateral position at the hip to articulate with the tibia near the centerline. The articular surface of the femur is angled to allow it to meet the horizontal tibial platform evenly, giving humans a knock-kneed appearance. This angle results in a valgus femur, a very distinctive morphology, compared with the bowlegged or varus chimpanzee knee (Fig. 28.4) (Hunt, 2015). Early ancestors had a more mobile knee with more rotation. In human knees are stable during walking with reduced rotation.

Human knee joints are enlarged to support the increased amount of body weight. With the increase in weight distributed on only two legs compared to quadrupeds, the knee requires more support to get enlarged. Due to the fact that the knees are situated almost directly under the torso, the amount of pressure is great which resulted in larger knee joints compared to hip joints.

A critical adaptation for efficient bipedalism relates to the need to keep the body's center of gravity balanced over the stance leg during the gait cycle. In humans, whose hips are wide apart, the shaft of the femur is angled so that the knee is closer to the body's midline than the hips. This angle is called the bicondylar angle, and the resulting knee joint is referred to as a valgus knee. The effect is to bring the knees closer together, placing the feet directly below the center of gravity. A result of the femur's bicondylar angle pulling the knees inward is that the tibia stands almost parallel to the line of gravity. Unlike the femur, the tibial shaft lies at a right angle to its proximal surface. Also of note, the human medial and lateral proximal articular condyles (i.e., the flattened surfaces on the top of the tibia that articulate with the femur) are relatively larger and elongated antero-posteriorly (i.e., longer front to back) compared to quadrupeds. The comparatively larger lateral proximal condyle (also seen on the femur and helps to create the bicondylar angle) is an adaptation to increased weight transfer through the femur and to the foot. In addition, modern human condyles are more concave and elliptical in shape to accommodate the elliptical femoral distal condyles. Quadrupeds' tibial condyles appear relatively spherical and are more convex. The elliptical shape in humans helps to lock the knee in place and create straight-forward leg movement.

Feet and toes

Along with the reorganized pelvis, the human foot is dramatically reorganized compared with the early ancestors (Hunt, 2015). The human foot has lost its gripping function, and instead the toes are in line so that all the toes are roughly parallel (Fig. 28.5). The calcaneus is relatively large and robust in humans as it contacts the ground first during bipedal gait. The robust size of the calcaneus provides stability and helps to absorb the high forces encountered during heel strike. The internal structure of the heel is spongy rather than solid to allow shock absorption. In addition, the shape of the calcaneus provides attachment points for strong ligaments that run from the arch of the foot to the tibia. These ligaments add support, creating a double arch system that helps to absorb stress as the foot hits the ground. Human feet have two arches. The hallux in humans is also much larger and more robust than the other four toes providing efficient toe-initiated push-off for propulsion. The fully adducted hallux in humans is commonly referred to as a non-opposable big toe.

In humans, the tibia's articular surface for the talus is situated relatively more inferior when compared to the anteroinferior orientation in quadrupeds. The talar superior articular surface which articulates with the distal tibia sits almost directly superior or nearly parallel with the talar body in humans. Plantar articulation surfaces on the talus (i.e., the calcaneal articular surface and the navicular

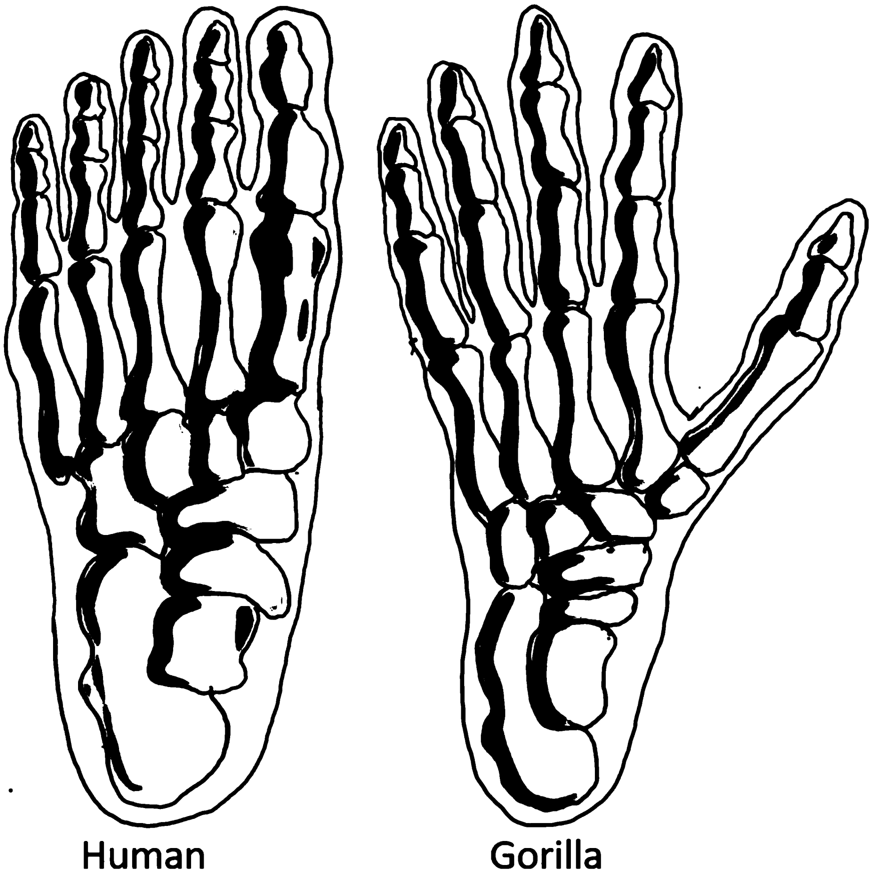

FIGURE 28.5 Chimpanzee and human feet.

articular surface) are also less angled than typically seen quadrupeds. Instead, these surfaces trend downward, forming a plantarly oriented foot when standing. Both the ankle and the subtalar joint are situated directly at the end of the tibia's long axis, which helps to transmit stress loads from the legs through the foot. Additionally, the relatively inflexible midfoot (under loading) and horizontal orientation of the ankle joint encourage a straighter foot path during walking. The talus is also relatively robust in humans, which helps to absorb stress during foot strike.

The human foot evolved to act as a platform to support the entire weight of the body. The adaptation of the feet to bipedal motion changed their function and structure. Size and shape also changed. Feet developed a wider and flatter structure that could act as a supportive platform. As there was no need for grasping or grabbing, the toes lost this ability and decreased in size. Hallux was gradually centered in line with the other toes but it maintained a larger size in comparison to the lesser toes for enabling push-off. Foot arches are important features that contribute to the propulsive system of bipedalism. Arches provide a more stable platform for the body.

Bipedal gait

No other living animal has similar locomotor pattern as in humans. During the evolution of plantigrade gait both the musculoskeletal system and locomotion generating circuits have been modified (Forssberg, 1995). Maintaining balance is critical when walking on two legs. Through the gait cycle, a biped must balance on one leg while lifting the other foot off the ground and swing it forward. Bipedal gait created well-known determinants to reduce the energy expenditure during walking such as heel strike, flexion of the supporting leg, intralimb coordination, pelvic movements (rotation, tilt, translation), muscle activities with specific temporal pattern.

In human gait, the prominent heel-strike and the push off at the end of the stance are of particular interest. In quadrupeds, calf muscles are active before heel strike and the main propulsive force occurs at the end of the stance due to increased activity of the quadriceps muscle. In humans active dorsiflexion during the end of swing is accomplished by pretibial muscles. The calf muscles contract first during the stance phase and produce the main propulsive force at the end of the stance phase. The importance of the calf muscles for forward propulsion in humans is reflected by a comparatively larger size and the design of the human foot with a longitudinal arch acting as a spring during push-off (Forssberg, 1995).

Humans are unique among apes and other primates in the musculoskeletal design of the pelvis and hind limbs. Our short, wide pelvis and long, heavy hind limbs both reflect our evolution. The common chimpanzee is a facultative biped and our closest living relative. O'Neill et al. reported that humans walk with a more stable pelvis than chimpanzees, especially in terms of tilting and rotational movements (O'Neill et al., 2015). These results demonstrate substantial differences between human and chimpanzee bipedal walking, in both sagittal and nonsagittal planes. Pontzer et al compared the kinematics, kinetics, and energetics of bipedal and quadrupedal walking and running in a sample of five captive chimpanzees (Pontzer et al., 2014). They reported that the spatiotemporal characteristics, joint angles, ground reaction forces, and metabolic cost of bipedal and quadrupedal locomotion are similar in chimpanzees.

Bipedalism is marked by several adaptive skeletal changes with certain costs. In spite of having highest intellectual capability, the design is vulnerable to scoliosis, osteoarthritis, and other musculoskeletal problems caused by axial -asymmetric- loading due to bipedal condition. The most spectacular alterations to support body weight and balancing are in spine, the pelvis, the skull and the feet. Low back and lower extremity joints are under extra stress in bipedal locomotion causing knee and back pain later in life. In females, adaptations in pelvis to walk upright make it difficult and painful to carry as well as deliver a baby with a large brain. Other disadvantages of bipedal gait are longer time to learn and inability to ambulate when one leg is injured. Moreover, because of pumping blood up instead of horizontally to heart and brain, risk of varicose veins in the legs is increased.

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Chapter 29

Kinesiology of the human gait

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Introduction

Gait can be defined as the use of each foot as a support to be able to move from point A to point B, never having both feet off the ground at the same time during walking gait. In order to walk like adults, an average child goes through a certain phase, which continues from 13 months to 7 years of age. During this process, the child falls, imitates its peers, stumbles, and finally learns how to move from one point to another by using both feet with a minimum amount of energy. As a matter of fact, if the whole human life cycle is taken into account, this period of nearly 6 years can be considered relatively short. However, the gait development cycle does not stop after 7 years of age. The music that is listened to (hip-hop, R&B, soul, jazz, metal, rock, etc.), momentary psychogenic state (gait after breaking up with the girlfriend/boyfriend, gait after passing an exam which it was thought as failed), walking with 20,000 dollars in the pocket, exhaustion, imitation of a very famous basketball player, etc. directly affect the way of one's walk. If the gait changes according to all these examples and other situations such as gender, geographical, age etc. differences, what is normal gait? The answer is quite simple. Available database defines the normal gait according to age with two standard deviation. This standard deviation accepts abnormalities as normal to a certain extent. In fact, there is a discrepancy in the result of nearly all studies on gait analysis because the obtained gait data may vary from one laboratory to another as the calibration, methods used, and joint center calculation techniques may change as well as individual differences (McGinley et al., 2009).

Gait is a common activity in our daily lives. People who experience pain in only one phase of gait do not feel it only once a day. If they take 7000 steps on average per day, they experience this pain 7000 times a day. This situation is unacceptable for the human body and, thus, causes automatic, compensatory changes in a short time. Therefore, only one phase of gait, or even a single problem in one joint, does not create problems only in that joint. Over time, it also causes problems in other segments. Thus, secondary and tertiary problems arise. The patient is often admitted to a gait analysis laboratory at this stage.

Gait

Gait, the most common activity in a human's daily life, includes between 5000 and 15,000 steps a day (between 2 and 5 million a year) depending on the level of activity (Silva et al., 2002). Even if a human being today takes 25% less steps compared to 10 years ago, the number of steps a human takes on average per day between 35 and 74 years of age is around 7000 (which fell from 11,900 to 6700 in men, and from 9300 to 7300 in women) (Sequeira et al., 1995). One of the reasons we are unsuccessful in our fight against inactivity and obesity might be the decrease in the number of daily steps taken.

In order to identify an abnormal gait tendency, normal gait variables must be defined using numerical data (Simon, 2004). The human eye, no matter how competent it is, is still incapable of analyzing the fast movements of all joint at the same time from all perspectives. Moreover, gait activity includes not only visible variables, but also include invisible variables such as moment, power, ground reaction force, muscle force, etc. Invisible variables are as important as visible ones because these variables are the ones that trigger movement.

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Understanding the normal gait is crucial

to identify the gait disorder more accurately.
to choose the correct treatment method.
to evaluate and document the treatment in a correct and objective way.
to compare different treatment techniques.
to propose a new treatment method.
to develop new treatment protocols.
to avoid errors resulting from the difficulty in remembering previous clinical observations.
to facilitate clinical discussions between colleagues by means of easily-accessible data.
to enable the easy identification of details that may be overlooked by the human eye as the gait cycle is quite complex and short.
to identify the difference between pathological and compensatory mechanisms during dynamical activities.
to better understand the patterns of motion. to carry out objective research.

Gait terminology

The gait cycle can be defined as the sequence of events that starts when one foot contacts the ground and ends when that same foot contacts the ground again. In fact, these two specific moments do not have to be the moments of contact with the ground. Instead, it the moment of choice may be the peak knee biggest flexion angle or any other particular moment you decide upon. However, these two specific moments should correspond to the same motion moment of the same body extremity. To facilitate matters, this first contact moment is chosen as the beginning of the process. The parameters necessary to formulate a general definition of gait are described below:

Concentric muscle contraction

Muscle contraction that increases the tension on a muscle as it shortens. It results in positive work and power production (Campbell et al., 2006).

Eccentric muscle contraction

Muscle contraction that increases tension on a muscle as it lengthens. It results in negative work and energy absorption. The effect of negative work and power absorption caused by the muscle is 6–9 times greater than positive work.

Isometric muscle contraction

Muscle contraction used for stabilization that does not generate net power (Campbell et al., 2006).

Kinematics

It describes the parameters of motion without using any terminology related to power. It deals with parameters such as linear or angular displacement, velocity, and positive acceleration (Campbell et al., 2006).

Kinetics

It describes the parameters that cause the motion. It deals with internal and external forces such as gravity forces, ground-reaction forces, inertia forces, muscle and ligament forces, joint power and moment (Campbell et al., 2006).

Ground reaction force (GRF)

It is the algebraic sum of the mass acceleration produced by all parts of the body during its contact with the ground. When a person's body weight falls on the foot during the stance phase, horizontal, vertical and rotational forces are exerted against the ground. For a clearer and briefer definition, ground reaction force can be defined with the following principle: when you step on the ground, it pushes back. This pushing force is called ground reaction force, a force vector whose direction, magnitude, and starting point may change at any moment. It is possible to measure this force by using the appropriate tools. The ground reaction force is equal in magnitude and opposite in direction to the force exerted by the foot on the ground during the stance phase. These forces create stress on the joints and can be controlled with muscle contraction. The ground reaction force can be measured using a tool called a "force plate" that is placed on the ground.

Joint moment (*M*)

A force exerted by a muscle or external sources creates a rotational motion at the joint, when it is applied to out of center of rotation. Therefore *M* (or torque) is equal to applied force and the distance between center of rotation and the point that where the force is applied (moment = force x distance). In the human body, moment is produced by external forces such as ground reaction force, gravity forces, and inertia as well as by muscle contractions, ligaments, and joint capsules (Ounpuu et al., 1991).

Moment of inertia

An object at rest remains permanently still and does not have the tendency to move. For instance, when two objects differing in weight are pushed towards the same direction with the same magnitude of force, they exert same amount of *M*, however the heavier object travels shorter distance. This moment is transferred by muscle contractions, ligament tensions, and joint contact surfaces in the human body (Rose and Gamble, 2006).

Joint power

It is related to energy absorption and production. In mechanics, power is defined as the work done per unit time. Joint power is determined by the net *M* acting on the joint and the angular velocity of the joint. Muscles are the primary structures in the body used for producing internal power. The muscles located near ligaments are sometimes capable of absorbing these internal powers resulting from internal processes of the body (Campbell et al., 2006).

Step length

A step is the motion that consists of a foot moving in front of the opposite foot (Baker, 2013). Step length is the linear distance between two feet. For example, the step length of the right step is the distance between the first point where the left foot contacts the ground and the first point where the right foot contacts the ground (Campbell et al., 2006) (Fig. 29.1).

Stride length

A stride is the time period between the moment of one foot contacts one point on the ground to moment of the same foot contacts another point on the ground, and involves propulsion of the center of gravity in the direction of motion. Stride length is the distance between two points where the same foot strikes the ground sequentially. This distance is the sum of left and right step lengths (Campbell et al., 2006).

Cadence (tempo)

It is defined as the steps taken per unit time. It is generally considered as the number of steps taken per minute (Campbell et al., 2006).

Gait speed

It is the distance traveled within a specific time period. Gait speed can be found by dividing stride length by the time spent for a single gait cycle or dividing the cadence by the step length (Campbell et al., 2006).

$$\text{Gait Speed} = \frac{\text{Cadence} \times \text{Stride Length}}{120}$$

It is important to note that stride length is shown as m/sec whereas cadence is the number of steps taken per minute. If these units are different, the number 120 will also change.

If the gait characteristics of two different case groups are compared, gait speed as a variable may not be a right choice because the gait speeds of these two groups maybe significantly different from one another unless both groups walk on a treadmill at the same speed. However, as walking on a treadmill is not based on the same dynamic rules as walking on the ground (White et al., 1998). Instead, selecting the cadence as a variable may give more accurate result when adjusted for two different groups for ground walking. Akalan et al. (2016a,b) were able to achieve very similar gait speeds and cadences in healthy adolescents using metronome after weakening their plantar - flexor muscle group. This method is widely used in the clinic; however, it takes some time to get used to the pre-determined tempo.

The gait cycle has certain energy generators. These are hip flexor and plantar flexor muscles (Gage et al., 1995). These energy generators as well as the muscles that ensure stability during the stance phase change their activation according to the gait speed. This is most clearly shown in surface EMG (electromyography) (Stoquart et al., 2008). According to studies conducted with the participation of healthy subjects, during walking both on the ground and on a treadmill, the activation of kinetic and kinematic changes of gait as well as the activation of the quadriceps, gastrocnemius, tibialis anterior, and hamstring muscles are changed with the gait speed (Stoquart et al., 2008).

Therefore, when conducting comparative studies, ensuring that the different groups have similar gait speeds will be an important convincing parameter with regards to the validity of findings.

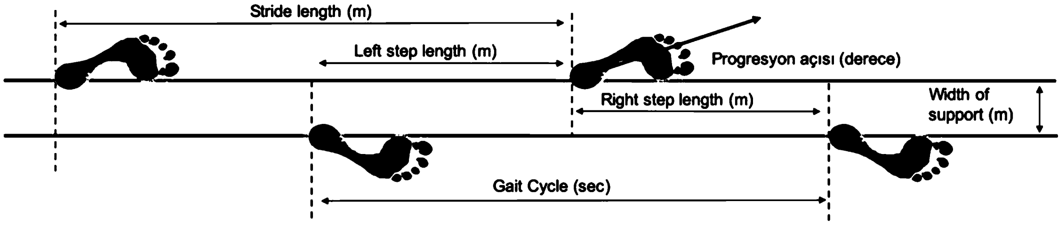


FIGURE 29.1 Demonstration of step length, stride length, and step width in gait cycle.

Duration of the stance phase

It comprises all sub-phases of the gait cycle, which begins when the foot contacts the ground and ends when the tips of the toes leave the ground. It is not very common to show the duration of stance phase in milliseconds. Instead, it is shown as a percentage of the gait cycle.

Duration of the swing phase

It comprises all sub-phases of the gait cycle, which begins when the foot advances ahead in the air and it is shown, just like the duration of the stance phase, as a percentage of the gait cycle.

Stride duration

Stride duration is mostly shown in milliseconds and it is accepted as 100% of the gait cycle. Therefore, the stance and swing phases are determined by taking the proportion of the millisecond duration of these phases to their percentage of stride duration (Baker, 2013).

Center of pressure (CoP)

It is the common center where the body weight applies pressure to the ground. It is also the point where the ground reaction force enters to the body (Perry, 1992; Craik and Oatis, 1995).

Gait development

In children, the gait starts before these requirements are fully acquired. For instance, it is normal for a 1-year old child who has just started to walk, to have an increased knee and ankle flexion at the swing phase, to start the stance phase using the sole and not to have an arm swing. However, the presence of these patterns in a 3-year old child is the sign of a neuromuscular disorder.

The gait of a child that has just started to walk is characterized by increased flexion at the knee and hips compared to an adult, increased step width, and absence of arm swing. The arms are in abduction while the elbows are in flexion and there are regular pauses. From a frontal view, the hips are at an external rotation during the swing. Moreover, the number of steps taken per unit time (cadence) is high, gait speed is low, and step length is shorter (Fig. 29.2).

In a 2-year old child, pelvic tilt and external hip rotation is decreased compared to 1-year olds; a greater knee extension is observed at the first contact; and a greater extension is observed in the hip and the knee when the toe tips are lifting off of the ground for the swing. The heel contact is observed at this age for most of the children. Moreover, the drop foot view that is observed in 1-year olds during the swing disappears at this age. Also, the arms start to swing and the step length decreases.

A 3-year old child displays a rotational joint movement that is similar to the adult gait pattern. High level of

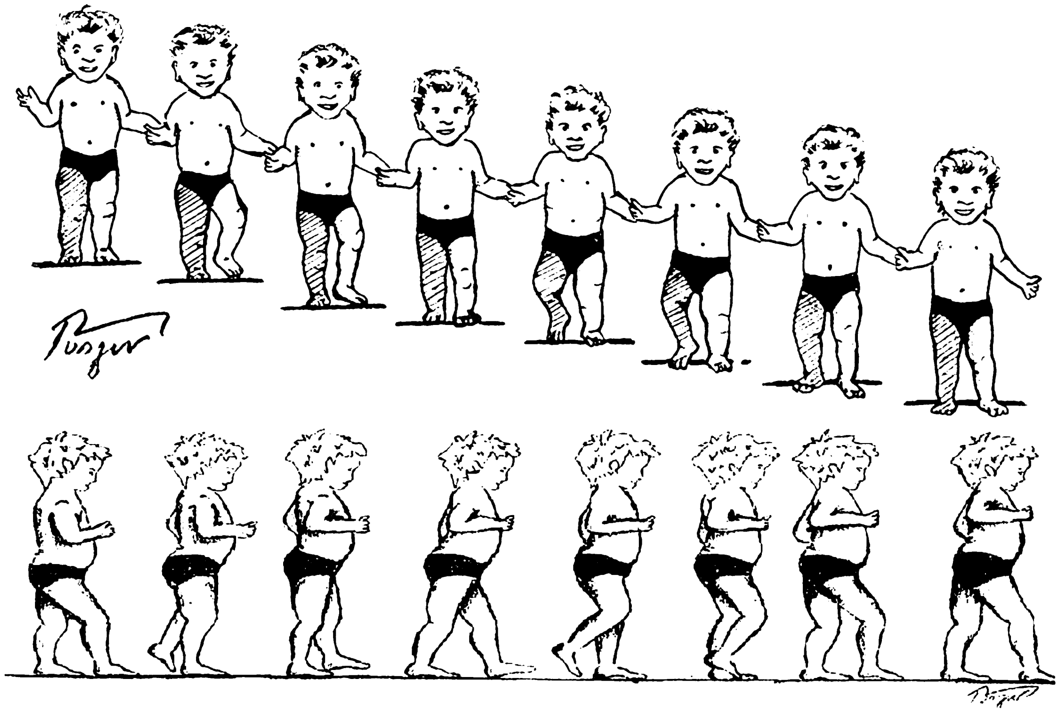


FIGURE 29.2 Full gait cycle of a one-year old child. Image of a gait that starts and ends with the contact of the right foot on the ground.

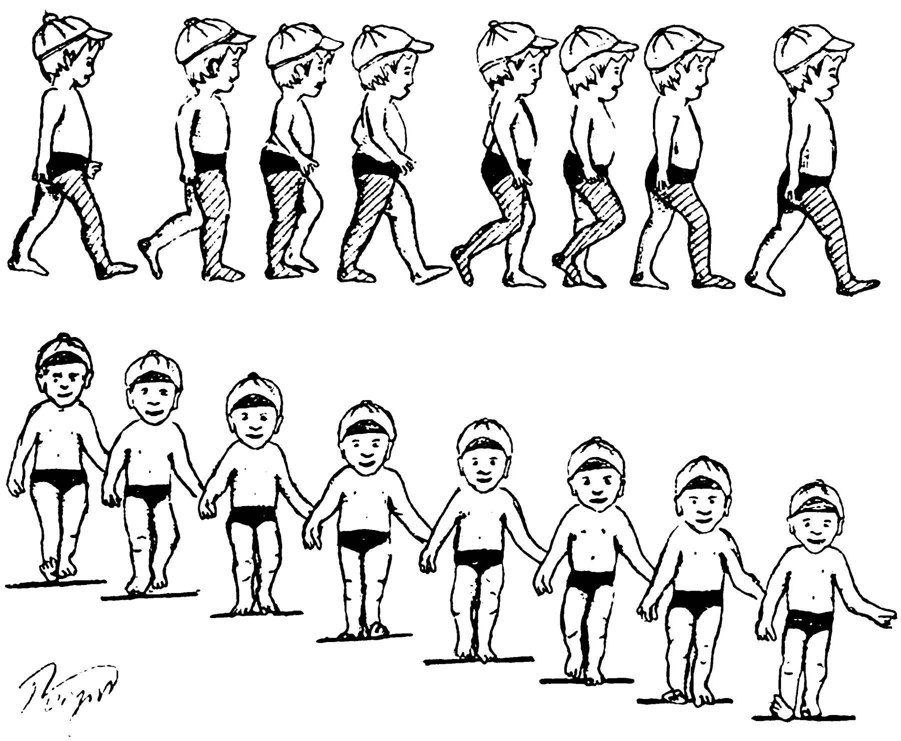


FIGURE 29.3 Full gait cycle of a three-year old child, characterized by arm swings, developed heel strikes, and a correct motion pattern.

cadence and low gait speed still continue at this age. The time spent for the stance phase is still long. The gait of a 3-year old child is mainly characterized with a better heel strike, reciprocal arm movements, more proper joint movements, narrow step width, and hip rotation the same as that of an adult (Fig. 29.3).

From age three to age seven, the child reduces its cadence, increases its step length, decreases the time spent for the stance phase, and increases its gait speed, thereby attains an adult gait pattern (Sutherland et al., 1988) (Fig. 29.4).

Normal gait

Normal human gait consists of consecutive basic extremity movements that aim to move the body from one point to another by preserving the stability, the appropriate energy consumption, and the shock absorption during initial contact with the ground (Wolfson et al., 1990). Normal gait requires normal MSS and peripheral neural system, metabolic activity, joint range of motion, muscle force and joint stability. Damage to one or several of these systems results in gait disorders, followed by a decrease in movement and independence in daily life (Imms and Edholm, 1981).

A typical gait cycle is divided into two main phases: the stance phase and the swing phase. The stance phase is the period in which the foot contacts the ground. The swing phase, on the other hand, is the period of time in which the foot is in the air. While the stance phase corresponds to nearly 60% of a typical gait cycle, the swing phase occupies about 40% of this cycle (Fig. 29.5).

A normal gait has five major requirements:

1. Stability at the stance phase
2. Capability to advance the foot forward
3. Appropriate position of the foot before the stance phase
4. Appropriate step length
5. Appropriate energy consumption.

Gait is considered pathologic if one of these requirements is not met (Gage, 1991). In order to fulfill these gait requirements, it is important to satisfy the following pre-conditions.

I. Stability requirements at the stance phase:
    1. stable foot on the ground during stance phase
    2. intact joint movements of lower extremities.
        a. allow the second leg to swing.
        b. in balanced condition
        c. allow the body to move forward.
        d. allow for an appropriate position of upper parts of the body,
    3. while standing, the center pf pressure (CoP) must be in the base of support the zone between the feet and must be advanced forward during gait.

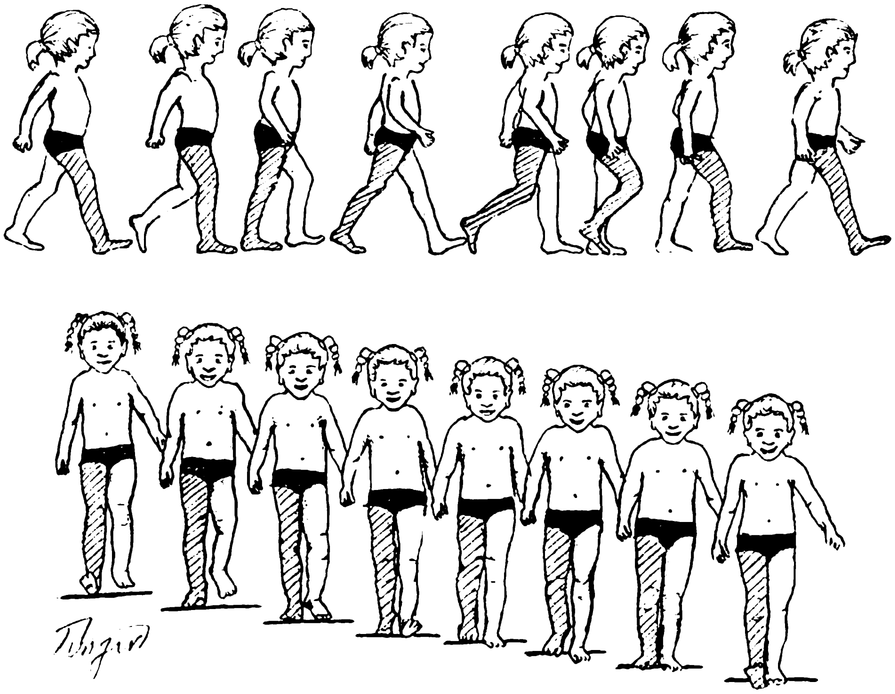


FIGURE 29.4 Full gait cycle of a seven-year old girl. Increased step length and adult-like gait pattern.

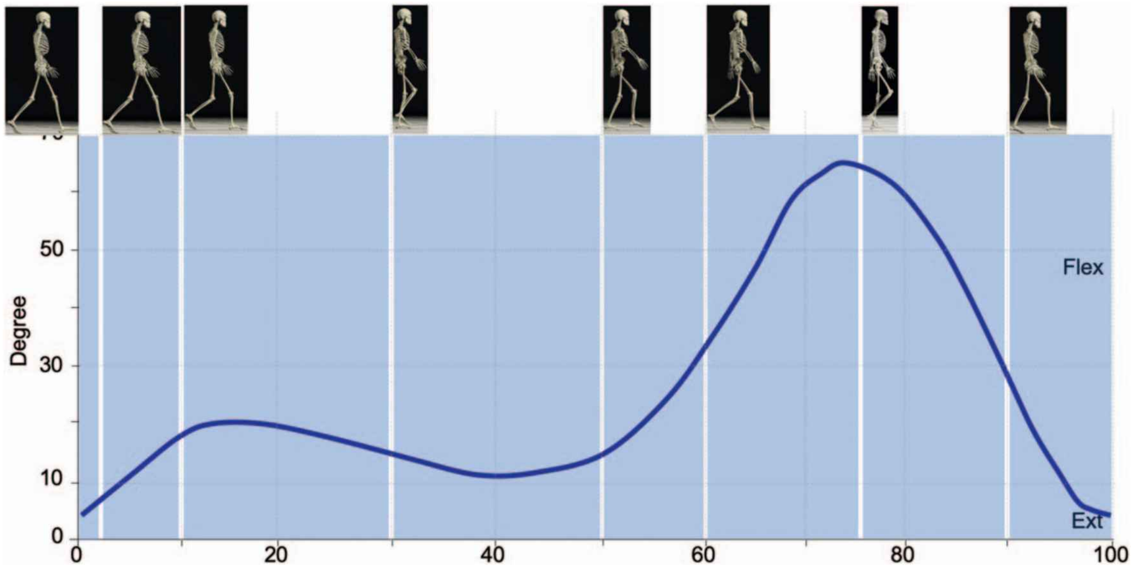


FIGURE 29.5 Gait phases and their synchronization shown on a sagittal plane knee kinematic graphic.

4. normal trunk stability.
5. appropriate body balance

II. Requirements for moving the foot forward during the swing phase:
   1. Stability at the stance phase.
   2. Normal position and moments acting on the ankle, knee, and hips at the stance phase.
   3. Sufficient ankle dorsiflexion, and knee and hip flexions during the swing.
   4. Sufficient body balance

III. Requirements for an appropriate position of the foot before the swing:
   1. Correct position and sufficient stability and moment at the stance phase.
   2. The following requirements must be met at the swing phase:
      a. Sufficient ankle dorsiflexion
      b. Balance between the foot invertor and evertor muscles
      c. Appropriate knee position

- d. Appropriate foot position
- 3. Sufficient body balance.

IV. Requirements for sufficient step length:
  1. The stance phase must be performed in a stable and appropriate position
  2. During the swing phase, the foot must be in a neutral dorsiflexion, inversion, and eversion.
  3. At the end of the swing, the knee must be able to perform a nearly full extension
  4. There must be sufficient hip flexion
  5. Body balance must be sufficient

V. Requirements for appropriate energy consumption:
  1. Certain biomechanical systems must be used. In order to do so:
     - a. The muscles must be inclined to lengthen rather than shorten during gait.
     - b. The muscles must be inclined to stretch before concentric shortenings (contraction by shortening) during normal gait as the "tension energy" returns.
     - c. The muscles that cover double joints are quite important as they generally serve as a belt for energy transfer.
     - d. The stability of joints must be ensured using the GRF and ligaments instead of muscle tension.

The movement of the CoG must be reduced as much as possible (Gormley, 1998).

Ankle rocker motions, which play an important role in moving the body forward and ensuring the energy flow, provide insight into the stance phase of the gait and especially into the ankle functions (Delp et al., 1990; Eastlack et al., 1991; Siegel et al., 2004). As defined by Perry, ankle rocker motions can be explained as below (Fig. 29.6).

1. Heel Rocker: It is the rolling movement that starts with the first contact of the heel with the ground and ends with the contact of the whole foot with the ground and it takes place with the eccentric contraction of ankle dorsiflexors.
2. Ankle Rocker: When the foot is stable on the ground, the tibia advances forward over the talus. This motion takes place with the eccentric contraction of gastrocnemius and soleus.
3. Forefoot Rocker: The heel leaves the ground and the pressure point advances towards the metatarsal bones and toes. This motion occurs with the concentric contraction of plantar flexors.

Methods in gait analysis

In the clinic, two types of gait analysis are performed. Ambulation profiles provide information on time-distance parameters and gait capabilities, while observational gait analysis is used in the assessment of kinematic and time-distance parameters (Krebs et al., 1985).

Ambulation profiles

An ambulation profile may be defined as a technique used to evaluate the gait behavior of a patient, a clinical evaluation of his/her locomotor capability (Nelson, 1974), or a quantitative evaluation method of the gait function. Ambulation profiles have been used for specific patient groups, such as patients with cerebral palsy (Reimers, 1972), patients with intense and medium neurological problems, amputee cases (Olney and Write, 1995), or for more general uses (Maluin, 1995).

While some profiles are graded with an ordinal scale, others determined the performances of the cases using interval scoring methods by means of variables such as time and distance (Nelson, 1974).

Reimers (1972) evaluated the performances of children with Cerebral Palsy (CP) in terms of their daily activities such as sitting, walking, and climbing stairs by using an ambulation profile based on the sum of global scores. Scoring was carried out according to the amount of help the children received during these activities (Reimers, 1972; Akalan and Temelli, 2014).

Another ambulatory evaluation system was developed as a functional scoring method, based on the amount of time and help necessary for walking on different types of surfaces (Reimers, 1972). This method evaluation form consisted of eight different ambulation situations, which

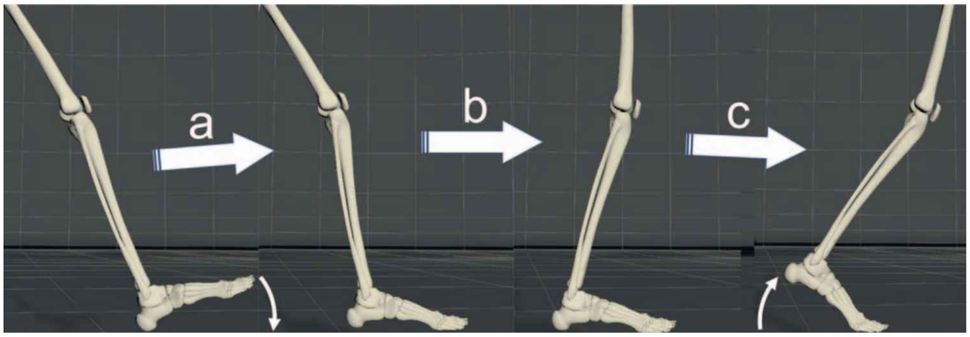


FIGURE 29.6 Foot rocker movements: (a) Heel rocker, (b) Ankle rocker, (c) Forefoot rocker.

differed according to the amount of help necessary for ambulation. The ambulation profile was scaled beginning from the least need for help (no help = 1) to the most need for help (ankle foot orthosis and walker = 8). Distances traveled by the patients on five different surfaces (ground, asphalt, carpet, ground with obstacles, and stairs) were measured. These surfaces were ordered from the easiest (ground = 0.1) to the most difficult one (stairs = 0.5) The duration needed by all ambulatory patients to cover each surface was recorded and then multiplied with an appropriate decimal number for each of the five surfaces.

A similar profile has been developed for amputee patients. This profile has fourteen sections. Basic gait capability (7 sections), free speed gait characteristics (3 sections), gait effort (3 sections), and gait endurance (1 section) are evaluated (Olney and Write, 1995).

Observational gait analysis (OGA)

Observational gait analysis (OGA) defines gait behavior in quantitative terms and is commonly used by clinicians. It helps to determine gait disorders in patients by using an observational method of evaluation. OGA helps to identify gait disorders and determine the degree of these disorders according to the decision of the observer (Krebs et al., 1985). Even though observational gait evaluation is carried out by most clinicians on a nearly daily basis, there is still no standardized observational gait analysis system used world-wide (Krebs et al., 1985; Maathuis et al., 2005).

The first OGA system was created by the Physical Therapy and Pathokinesiology Service of Rancho Los Amigos National Rehabilitation Center in the state of California in the U.S. As it was prepared by taking into consideration many details, the system has since been the most frequently used OGA system in the world (Perry, 1992). Perry stated that it is necessary to learn well how to assess the ankle, knee, and hip joints. The findings are interpreted as total leg function by summing up all deviations in every single gait sub-phase. The OGA system of Rancho Los Amigos was also quite useful in drawing up the appropriate treatment plan for patients. However, even though this system has been used for years, no study has been reported yet on the reliability or validity of Rancho Los Amigos' OGA system (Perry, 1992).

Other gait deviation analysis systems focus particularly on gait abnormalities caused by individual disease categories. For instance, there are analysis systems for specific diseases such as hemiplegia (Reimers, 1972), rheumatoid arthritis (Maluin, 1995) and lower limb amputations. With time, physical evaluation findings and treatment objectives were added to these forms, which facilitated the process of making decisions on the initiatives undertaken and drawing up treatment plans in order to eliminate gait disorders (Maathuis et al., 2005).

Few studies have been conducted on the reliability and validity of OGA (Table 29.1). In these studies, the findings show generally a medium level of reliability even though different methodological approaches were used in each study. Similar findings recorded in many different parts of these studies point to the possibility that it is still too early to consider OGA as a reliable method to be used in clinics (Maluin, 1995).

In the Edinburgh Visual Gait Analysis system, one of the latest reliability studies on the subject, researchers examined the motions of the legs, knees, hips, pelvis, and trunk during both stance and swing phases (Maathuis et al., 2005).

Recorded video may be used in clinics as another observational gait analysis method. When recording in the sagittal plane, it would be useful to i) focus the video camera on at least the area with 3-meter width on the wall and ii) advise the patient to walk on a straight line on the walkway by giving him/her the instruction to "walk towards the opposite wall in the same way as he/she would do outside," starting from first left and then the right side of the walkway.

Analysis can be made watching video as assessors observe the patient as if they are in real clinical setting. The assessments on motion changes are based on the following definitions:

Normal: Movement of the joint within the normal movement limits necessary for normal gait function.

Moderate abnormalities: Transgression by the joint of normal movement limits necessary for a normal gait function at a noticeable level. A change of between 10° and 15° in a normal movement of the knee joint during gait can be given as an example.

Marked abnormalities: Transgression by the joint of normal movement limits necessary for a normal gait function at a very noticeable level. A change of more than 15° in a normal movement of the knee joint during gait can be given as an example.

Kinematic analysis

It deals with the motion parameters that show a kinematic character in gait analysis. These parameters are described by defining the body in certain solid segments. This analysis serves to describe the joint motion spaces between different body segments and parameters such as velocity and acceleration, without using any term related to power. The data is analyzed separately in sagittal, frontal, and transversal planes (Krebs et al., 1985; Akalan and Temelli, 2014). In gait analysis laboratories, it is possible to measure the angular velocity and acceleration of joint

TABLE 29.1 List of studies conducted on the reliability and validity of observational gait analysis.

Study	Pathology	Observer	Scoring type	Data type	Statistical analysis	Study type
Goodkin and Diller (1973)	Hemiplegia	PT. N = 3	Ordinal	Live	Percentage compliance	Reliability
	N = 10		3-point scale			
De Bruin et al. (1982)	Cerebral Palsy	Orth. Asst.	Ordinal	Video	None	Reliability
	N = 18	N = 6	3-point scale			
Miyazaki and Kubota (1984)	Hemiplegia	Mixed	Ordinal	Live	Pearson	Reliability
	N = 48	N = 5	4-point scale		Correlation	Validity
Saleh and Murdoch (1985)	Amputee	Mixed	Nominal	Live	Percentage compliance	Validity
	N = 5	N = 4				
Krebs et al. (1985)	Bilateral KAFO	PT	Ordinal	Video	Percentage compliance	Reliability
	N = 15	N = 3	3-point scale		SEM, ICC	Validity
Patla and Clous (1998)	Heterogeneous	Kins. S.	Nominal	Video	Correct/Incorrect	Reliability
	N = 8	N = 5				
Eastlack et al. (1991)	RA	PT	Ordinal	Video	Kappa et al. ICC	Reliability
	N = 3	N = 54	3-point scale			
Akalan (1999)	SP	PT	Ordinal	Video	Kappa et	Reliability
	N:41	N = 3	3-point scale		Percentage compliance	
Maathuis et al. (2005)	N = 24	PT	Ordinal	Video	Kappa	Reliability
		N = 3	5-point scale			

PT: Physiotherapist; Orth. Asst.: Orthopedic Assistants; KAFO: Knee Ankle Foot Orthosis; SEM: Standard Error of Measurement; ICC: Intraclass Correlation Coefficient; Kins. S: Kinesiology Students; RA: Rheumatoid Arthritis.

movement of the trunk, pelvis, hip, knee, and ankle on these three planes.

Reflector markers are placed on certain points of the body (Fig. 29.7A). (At least three markers must be placed for each segment. Three markers are enough to identify all motions of a segment in 3-D space). These markers are observed using high-speed cameras. The cameras are surrounded by flashers, which work in synchronization with the cameras. In each frame, these flashers shine on the markers. The camera picks up these shining markers and sends them to the computer for signal processing. Then, the computer draws a stickman figure using this data (Fig. 29.7B). It actually draws a specific stickman for each case particular characteristic (height, weight, segment anthropometry). These stick figures are basically versions of an existing mathematical model that are modified using physical characteristics of the case. Lastly, kinematic graphics are created in the frontal, sagittal, and transversal planes, as shown in Fig. 29.7C (Krebs et al., 1985; Cutlip et al., 2000; Gage, 2004).

Kinetic analysis

It is quite hard to perform the kinetic analysis without using technological tools. In this analysis, it is important to measure the ground reaction force. If magnitude, direction, and starting point of a force vector are known, its perpendicular distance from the joint center by means of the projections on each plane can be calculated. Thus, the instant moment (*M*) on each joint can be found for each moment of the gait cycle. It can be assumed that when a joint center is recorded with a video camera of 1000 Hz. (i.e. 1000 frames per second), the camera is able to find the location of the joint center once in each millisecond. If GRF is at the same frequency, *M* that is created at the relevant joint should be found once per millisecond.

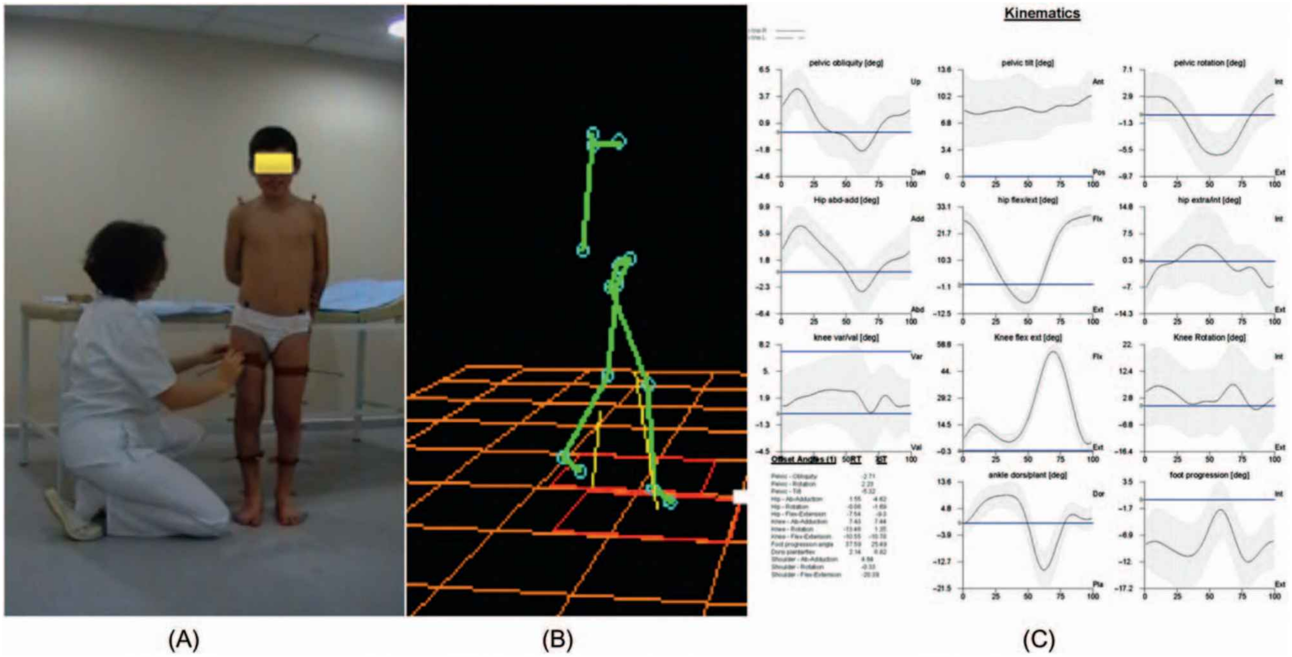


FIGURE 29.7 Kinematic analysis. (A) Marker placement, (B) Skeleton projection of the stick figure, (C) Kinematic graphics.

When this *M* is multiplied by the joint angular velocity for each plane, the force (F) acting on the joint can be found. (the joint angular velocity may be calculated by means of first derivative with respect to time of the angle recorded with cameras). Internal forces should be able to react against the GRF to stabilize the joint in a specific position. It means that the *M* created on the joint by the GRF is equal, but opposite to the moment created by muscles, ligaments, and other internal forces at that specific moment and motion pattern. Thus, once the GRF is calculated for that specific moment and joint angle, the internal moment created for that specific moment can be known.

GRF requires the pressure-sensitive plates (force platforms), which measure the total force exerted by the foot on the ground. These platforms measure the GRF according to Newton's 3rd. Law using piezoelectric or strain gauge sensors that show the starting point, direction, and the magnitude of the GRF when stepped on them (Krebs et al., 1985; Perry, 1992; Whittle, 1996), (Fig. 29.8)

Electromyography (EMG)

As muscle activities cannot generally be evaluated with the naked eye, they are examined by means of electrodes placed on the skin (surface EMG) or in the muscles (needle EMG). Dynamic electromyography is used to measure muscle action potentials during gait (29). As the EMG measures the electrical activity, and not the mechanical activity in the body, it is not used for making a distinction among concentric, isometric, and eccentric contractions or for associating the electrical activity with the contraction force (Whittle, 1996; Kanatli et al., 2006).

EMG does not able measure the muscle force, or the power acting on the joint if it is not treated in a signal processing system. In fact, if y EMG is not used in a laboratory for scientific purposes, it is only used for determining when the muscle activity starts and ends.

In order to examine muscle activity during gait, EMG electrodes are often placed on the motor points of the muscles during a dynamic EMG application (Fig. 29.9). This is done in order to acquire information on the action potentials of motor units, examine myoelectric activity of the muscle during gait (Fig. 29.10). The surface electrode usage is common in most of the gait laboratories (Delp et al., 1990). Skin preparation is necessary before attaching these electrodes in order to reduce the intense resistance of the skin.

Energy consumption

During gait, energy is consumed for acceleration, braking, and shock absorption. For shock absorption and braking, 8 units of energy are consumed while only 5 units are consumed for acceleration. Normal gait is an economical process in terms of energy consumption; however, the consumption increases considerably during abnormal or pathologic gait. The most useful way to calculate the energy consumption is to measure the oxygen consumption (Delp et al., 1990; Wolfson et al., 1990; Gage et al., 1995). Energy consumption is calculated by measuring the oxygen requirement, carbon dioxide production, or heart rate and gait speed using a 6-minute walk test.

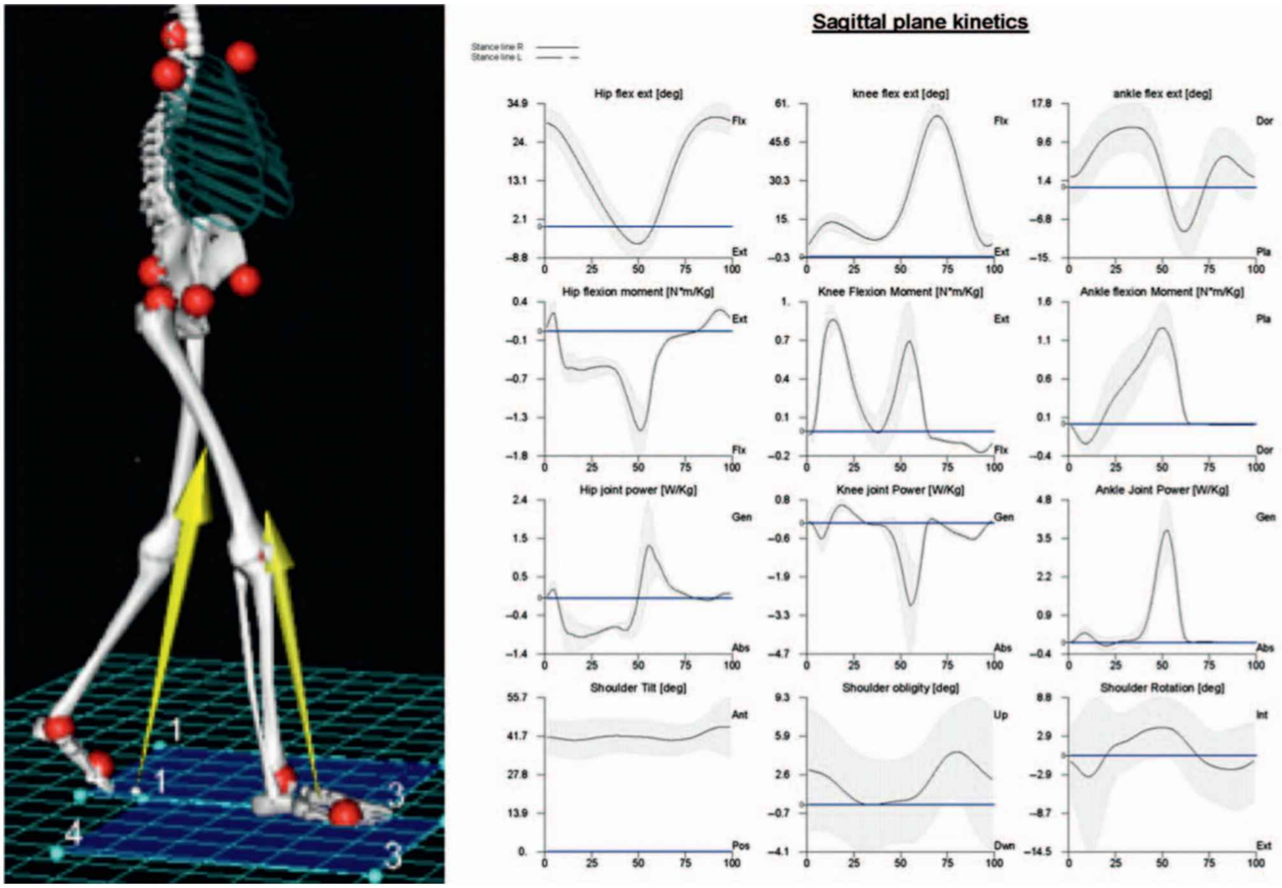


FIGURE 29.8 Ground reaction force and kinetic analysis graphics.

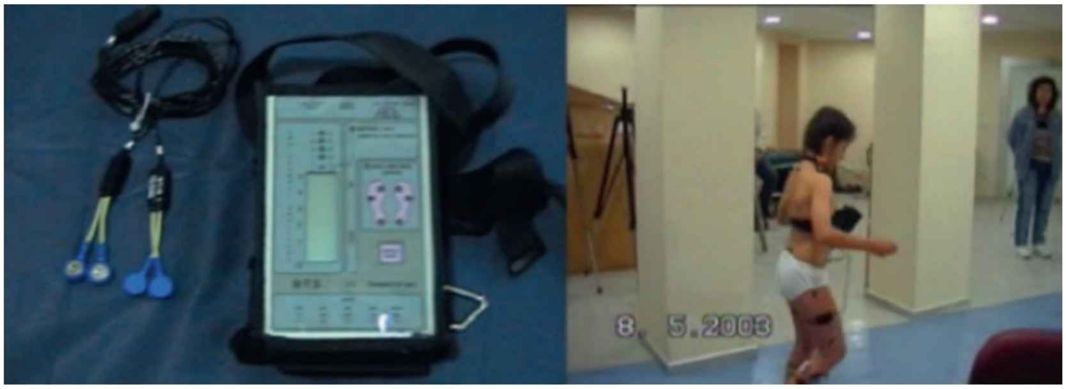
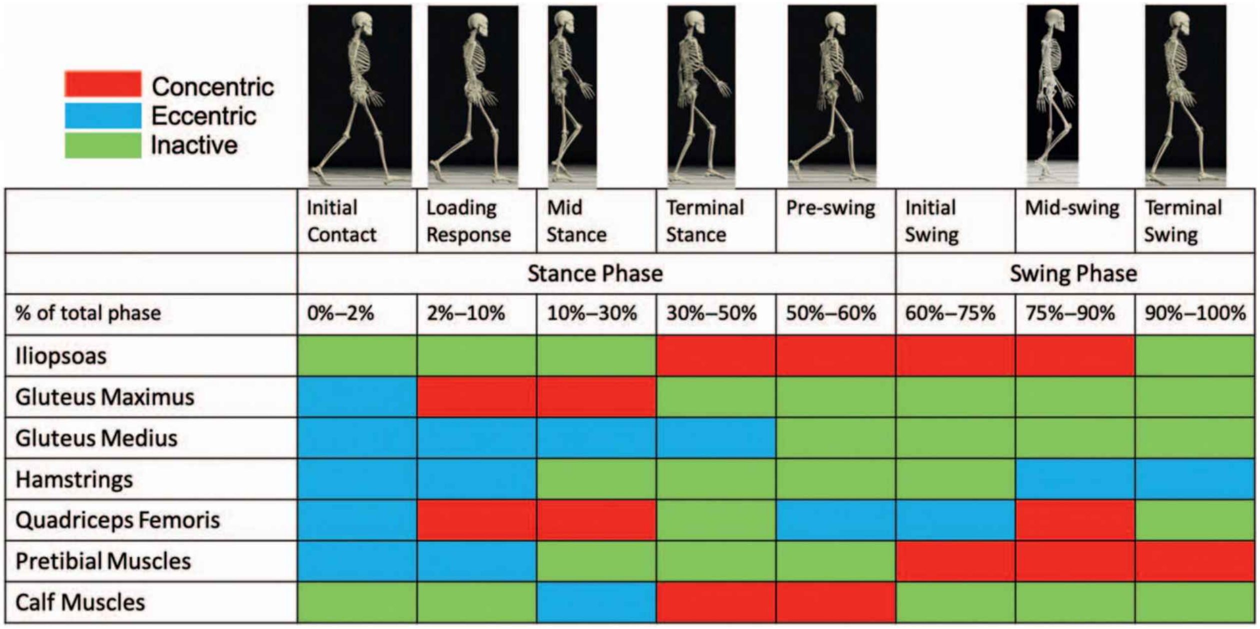


FIGURE 29.9 Dynamic telemetric EMG and its application in gait analysis.

Another method of energy consumption evaluation during gait is to calculate the inverse dynamics of kinetic and kinematic data (Sequeira et al., 1995).

Plantar pressure analysis

The load distribution under the foot is like the tip iceberg of gait. Pressure distribution on the sole is literally a demonstration of all activities happening above the sole (Fig. 29.11). Another source of data regarding plantar pressure analysis is the center of pressure (CoP). In fact, this center shows the point where the GRF enters our body. As body stance on the ground changes momentarily with every single movement, it is possible to observe the change of this center while standing or walking (Fig. 29.12). This information is used both before and



🟥 Concentric
🟦 Eccentric
🟩 Inactive

	Initial Contact	Loading Response	Mid Stance	Terminal Stance	Pre-swing	Initial Swing	Mid-swing	Terminal Swing
	Stance Phase					Swing Phase		
% of total phase	0%–2%	2%–10%	10%–30%	30%–50%	50%–60%	60%–75%	75%–90%	90%–100%
Iliopsoas	🟩	🟩	🟩	🟥	🟥	🟥	🟥	🟩
Gluteus Maximus	🟦	🟥	🟥	🟩	🟩	🟩	🟩	🟩
Gluteus Medius	🟦	🟦	🟦	🟦	🟩	🟩	🟩	🟩
Hamstrings	🟦	🟦	🟩	🟩	🟩	🟩	🟦	🟦
Quadriceps Femoris	🟦	🟥	🟥	🟩	🟦	🟦	🟥	🟩
Pretibial Muscles	🟦	🟦	🟩	🟩	🟩	🟥	🟥	🟥
Calf Muscles	🟩	🟩	🟦	🟥	🟥	🟩	🟩	🟩

FIGURE 29.10 Activity of muscles during gait. Green colour shows that muscles are inactive, blue color shows eccentric contraction, and red colour shows consentric contraction.

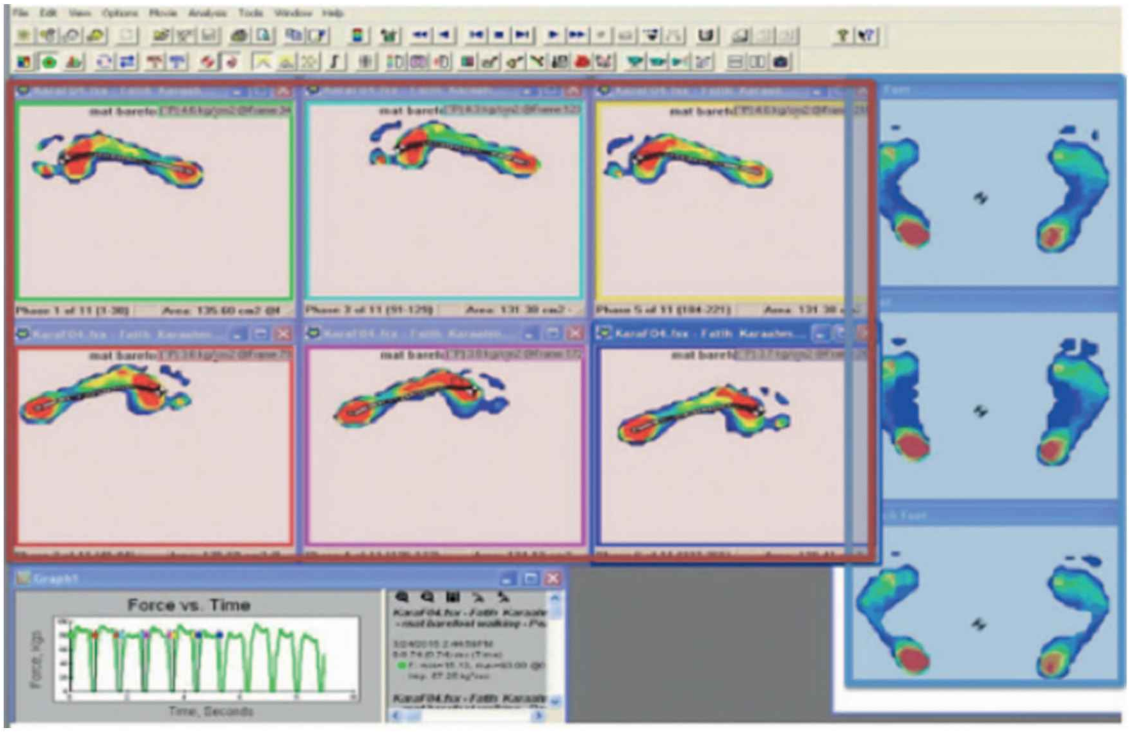


FIGURE 29.11 Example of plantar pressure analysis. The blue frame shows plantar pressure during standing, and the red one shows pressure during gait. The green graphic shows the momentary changes in the vertical force of the foot (10 steps).

after the treatment to evaluate the load distribution changes among different treatments and to identify an appropriate insole for the patient (Gage et al., 1995; Sequeira et al., 1995).

Physical evaluation and functional scales

A gait analysis cannot be performed without proper physical evaluation. There may be differences between these measurements and those performed during gait. Most of the

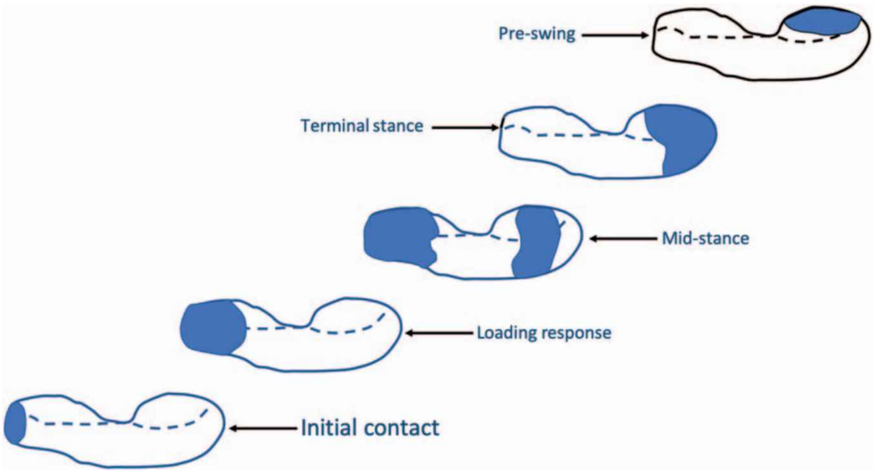


FIGURE 29.12 Plantar pressure zones during gait. The dashed line shows the trajectory of the CoP.

measurements at the lying position rely on static conditions, which is carried out without a joint movement or GRF. Therefore, gait pathology or compensatory changes cannot be estimated only through physical evaluation. However, it is necessary to include appropriate physical evaluations in the gait analysis to report about the patient and the disease. For instance, in the physical evaluation of a child with cerebral palsy, spasticity evaluation and selective motor control play a leading role in addition to active and passive ranges of motion. Meanwhile, in the physical evaluation of a patient with a muscle disorder, it is more important to evaluate the muscle force and passive range of motion, rather than the spasticity. Furthermore, the application of functional motion scales (gross motor evaluation tests, etc.) as well as balance and coordination tests change according to the patient and disorder (Gage, 1991; Davis, 1996; Gage et al., 2009).

Gait sub-phases

The gait cycle is divided into 8 sub-phases. These subphases allow the body to move forward without energy loss. In fact, we can compare ourselves to a car in order to understand how we minimize the energy loss during gait. While moving from a point A to a point B, a car's center of gravity follows a linear pattern by means of its wheels. However, as a person prefers to walk on two feet, it is not possible for his/her center of gravity to be linear. The closest curve to a line is the sinusoid (sine wave) (Fig. 29.13). If we maintain the peak amplitudes of this sinusoid at certain intervals, this curve looks like a line, which allows us to consume less energy. In this way, when we ensure a harmony of movement between the pelvis, hips, knee, and ankle (Table 29.2), we can maintain pelvic rotation at 4°, internal and external rotation at (4° + 4°) 8°, pelvis obligation at 5°, and the lateral displacement of body's center of gravity at 4–5 cm (i.e. amplitudes of the sinusoid for each plane) and walk on two feet with a minimum level of energy consumption. In order to achieve this, during the stance phase, the leg moves with the kinematic values given in Table 29.2.

Initial contact

Time period: 0%–2%

Task: Weight loading

Critical aspect: Initial contact of the foot with the ground occurs with the heel strike.

Kinematics:

1. Hip flexion 30°
2. Knee neutral position 0°–5°
3. Ankle position 0° (Fig. 29.14)

Active muscle group:

1. Gluteus maximus control the flexor moment created by the GRF.
2. Hamstrings prevent hyperextension of knee joints and help to control the flexion moment at the hip joint.
3. Tibialis anterior starts the heel strike.

It is the initial contact of the foot with the ground. This phase is generally carried out with the heel. This phase is not called "heel strike phase" because not everybody is capable of initiating the gait cycle using their heel. This phenomenon is explained by James R. Gage as follows: "The foot is like a plane. Excessive dorsiflexion at the initial contact would damage the plane's tail end; excessive valgus or varus would damage the wings; and stepping in plantar flexion would damage the nose of the plane" (Gage, 1991). Although this phase is short, it is observed as a noise in the force platform. It is actually caused by the impact of the rapidly advancing foot to the ground during the initial contact, even though it tries to slow down. Therefore, the ground reaction force moves as shown in Fig. 29.14 (Perry, 1992; Kauffmean and Sutherland, 2006; Gage et al., 2009). This change is also

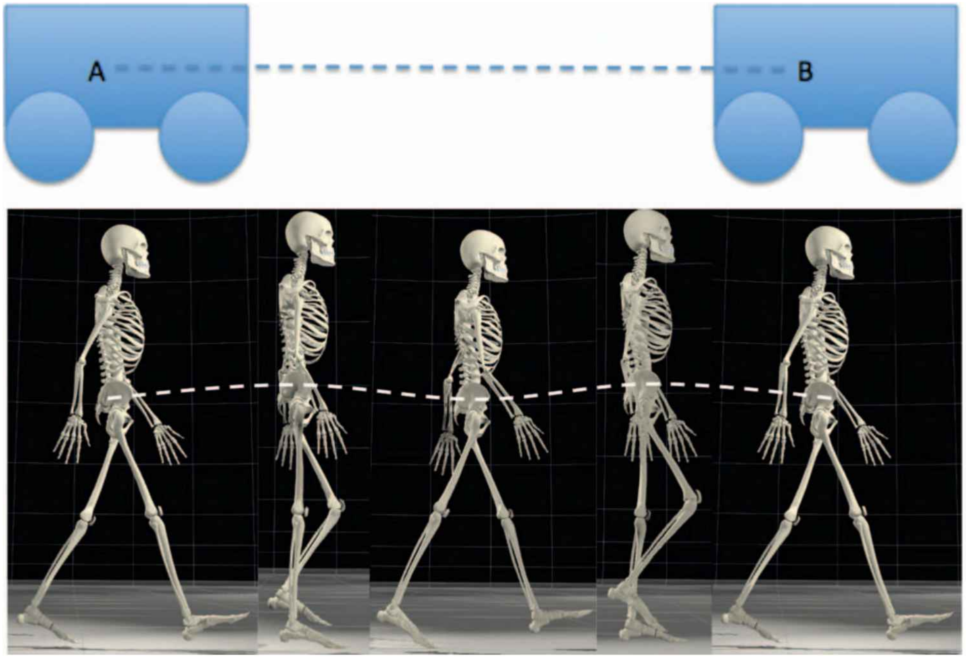


FIGURE 29.13 Energy conservation in the body by means of a sinusoidal curve of body's center of gravity during gait.

TABLE 29.2 Summary of lower extremity movements during the gait.

	Early Stance		Mid Stance	Terminal Stance	
Reference Extremity	Initial contact	Loading response	Mid stance	Terminal stance	Pre- swing
Hip	Flexion 30° ⟶	⟶	Extension 0°	Hyperextension 10° ⟶	Flexion 0°
Knee	0° ⟶ Flexion 15°	⟶	Extension 0° ⟶	⟶ Flexion 35°	
Ankle	0° ⟶ Plantar Flexion 15° ⟶	⟶	Dorsiflexion 15° ⟶	⟶ Plantar Flexion 20°	

known as heel transition. Thus, the GRF at the initial contact goes through a point very close to the ankle, knee, and hips. The knee extension at this phase takes place with two mechanisms. First, the GRF goes through the front of the knee during most of this sub-phase and exerts a moment on the knee towards its extension. Secondly, the vastus group controls the motion and the ilio-tibial band creates a tension together with the gluteus maximus activity. This activity of gluteus maximus also prevents excessive flexion of the hips. At this phase, 10%–20% of the maximum muscle power (MMP) together with the hamstring contraction prevent the knee from hyperextending (Perry, 1992). In the distal part, dorsiflexor muscles (tibialis anterior toe extensors) are active in order to facilitate the absorption of the shock (Fig. 29.15).

In the coronal plane, the GRF shifts towards the medial of the hips, which requires the activation of the hip abductor muscles in order to control this force. The knee goes through abduction throughout the whole stance phase, starting from the initial contact.

Loading response

Time period: 2%–10%

Task: Weight loading, shock absorption (primarily, by three vastus of the quadriceps), maintaining the forward movement.

Critical aspect: Plantar flexion of the ankle while maintaining the hip stability and control of the knee flexion.

Kinematics:

1. Hip flexion 30°
2. Knee flexion from 0° to 15°
    a. Ankle plantar flexion from 0° to 15° (Fig. 29.16)

Active muscle group:

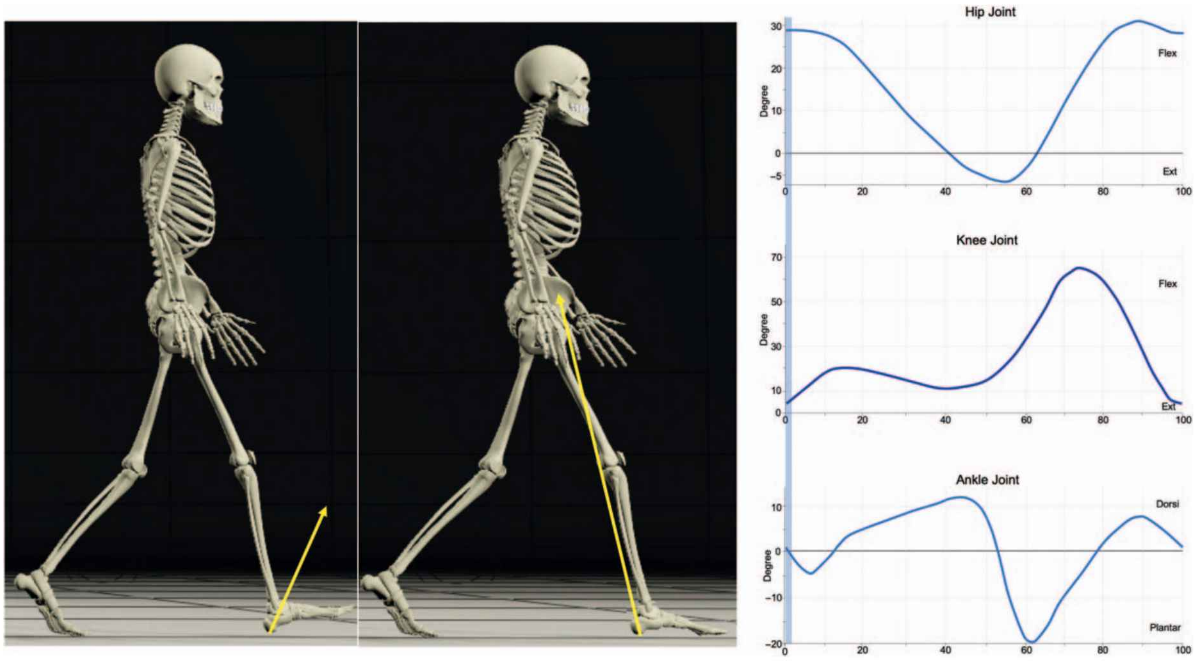


FIGURE 29.14 Initial contact and its kinematic projection. The blue area shows the related sub-phase.

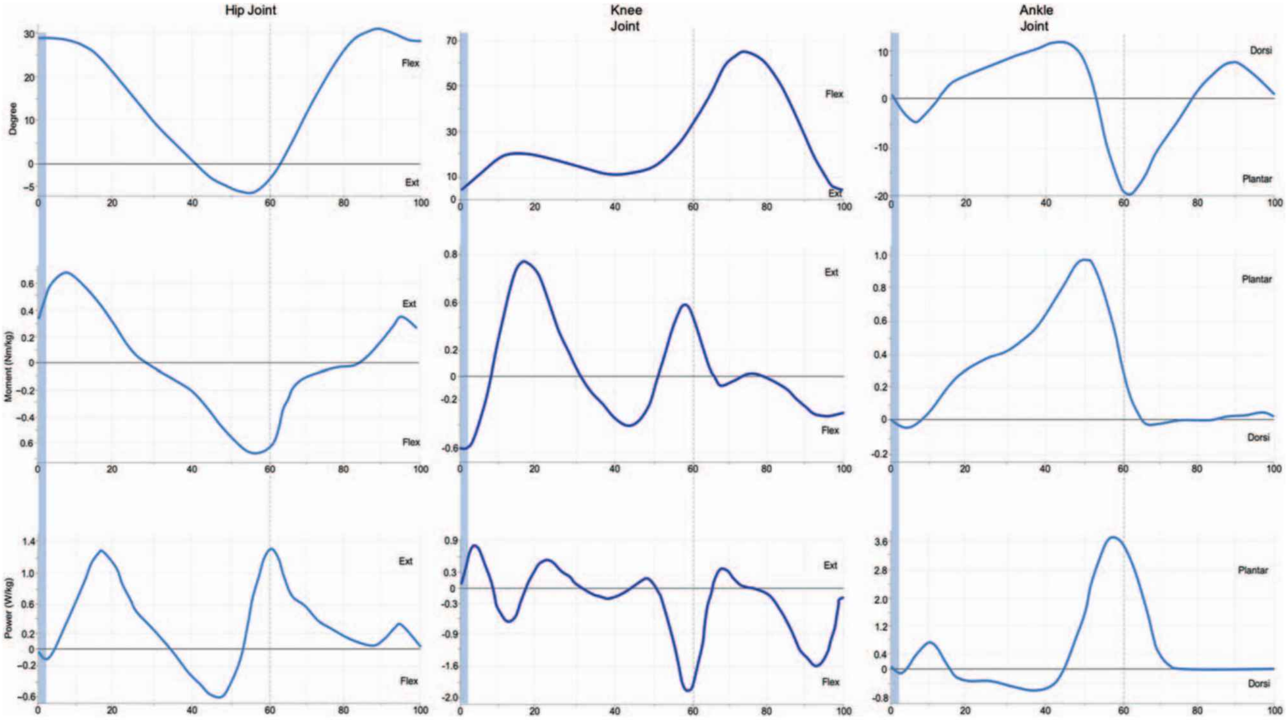


FIGURE 29.15 Initial contact kinetic attitude. The blue area shows the related phase, the red line shows the moment at which the toe tips leave the ground.

1. Hamstrings are contracted concentrically for a short time at low amplitudes in order to prevent a full locking of the knee.
2. Tibialis anterior slows the landing of the foot and cause a flexion in the knee by pulling the tibia forward through the body's center of gravity line.
3. Quadriceps (three vastus) are contracted eccentrically to reduce knee flexion and absorb the shock created during the foot contact.

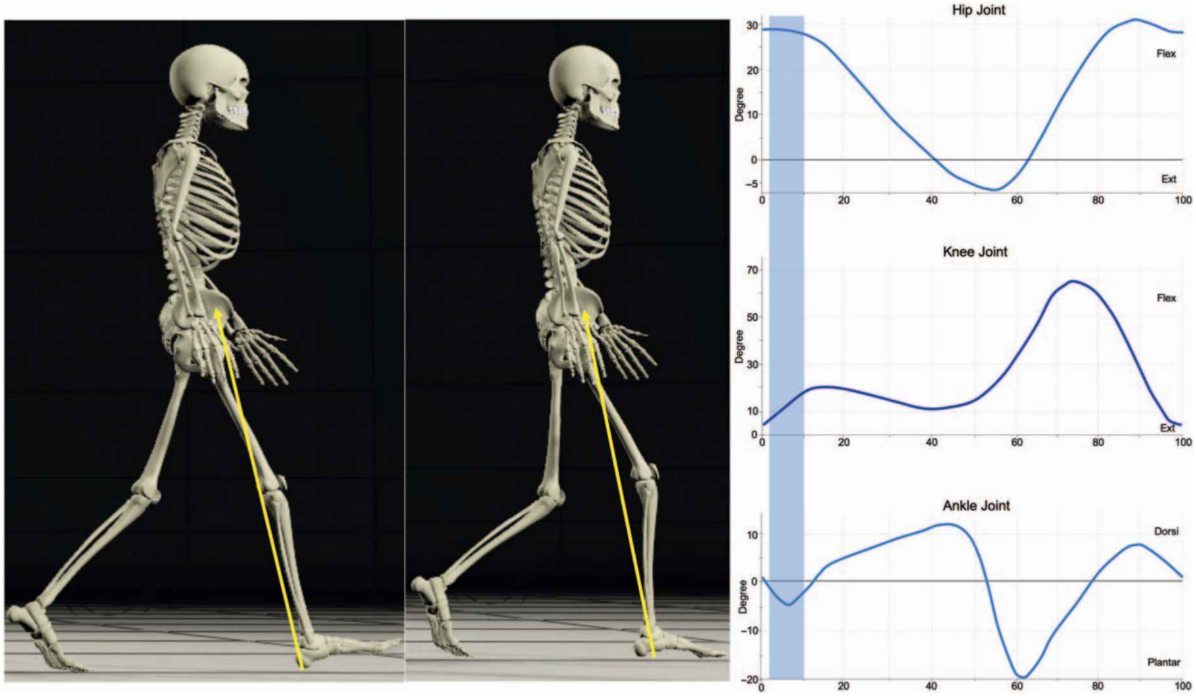


FIGURE 29.16 Loading response and its kinematic projection (from top to bottom, respectively, pelvis, hip, knee, and ankle, y: degree °, x: % gait cycle). The blue area shows the related sub-phase.

4. Gluteus maximus allow the body to accelerate on the femur by causing a concentric contraction in the hip extensors. Meanwhile, the ilio-tibial band helps knee extension.
5. Adductor magnus allows the forward movement of the pelvis over the foot during the stance phase as well as its internal rotation.
6. Gluteus medius reduces decline of the pelvis on the opposite side by causing an eccentric contraction in the hip abductors.

This sub-phase takes place during the period starting from the first heel strike until the moment the foot leaves the ground. It occurs before the swing phase of the opposite foot. The main purpose is controlling the loading process of the foot. Femur tries to catch up with the rapid advance of the tibia, but it fails to do so. It causes the GRF to go through the back of the knee (Perry, 1992). Thus, it goes slightly through the front of the hip and the ankle. At this sub-phase, CoG is at the lowest level as it moves vertically in the gait cycle. The highest level is observed at the mid-stance sub-phase (Perry, 1992; Gage et al., 2009). The GRF, which reaches up to the 120% of the body weight at the initial contact, is absorbed at this sub-phase especially with the critical motions of the ankle and the knee (Gage et al., 2009).

At this sub-phase, the knee extensors (vastus medialis, lateralis, and intermedius) are contracted eccentrically to be able to control the excessive flexion of the knee and maintain the knee flexion at around 15–20° (Perry, 1992). As the biceps femoris (whose main task is to prevent a hyper-extension in the knee) is not active at this phase, the task of vastus to control the flexion becomes more important. Rectus femoris muscle is not active because it is considered as a hip flexor and its contraction already increases the hip flexion that must be controlled in this phase (Nene et al., 1999). As a matter of fact, whether the rectus femoris is a real part of the quadriceps femoris is still subject to debate. This distinctive attitude during gait, and its difference as a hip flexor compared to the vastus may be distinguished during dynamic activities. Some categorize quadriceps as divided into triceps femoris and rectus femoris (Nene et al., 2004).

Another important muscle group is plantar flexors. At this phase, plantar flexors are contracted eccentrically in order to prevent the tibia from advancing rapidly over the talus and thus protect the knee from excessive flexion. Therefore, in the closed kinetic chain, plantar flexors play a role as a knee extensor (Kauffmean and Sutherland, 2006) (Fig. 29.17)

During this sub-phase, the necessity of a high level of stabilization of the hip joint in the coronal and sagittal planes requires increased gluteus maximus and medius activity. At the end of this sub-phase, gluteus medius elevates the opposite side of the pelvis to its highest position. In the hip, gluteus maximus (25% MMP) together with the adductor magnus (40% MMP) helps achieving hip

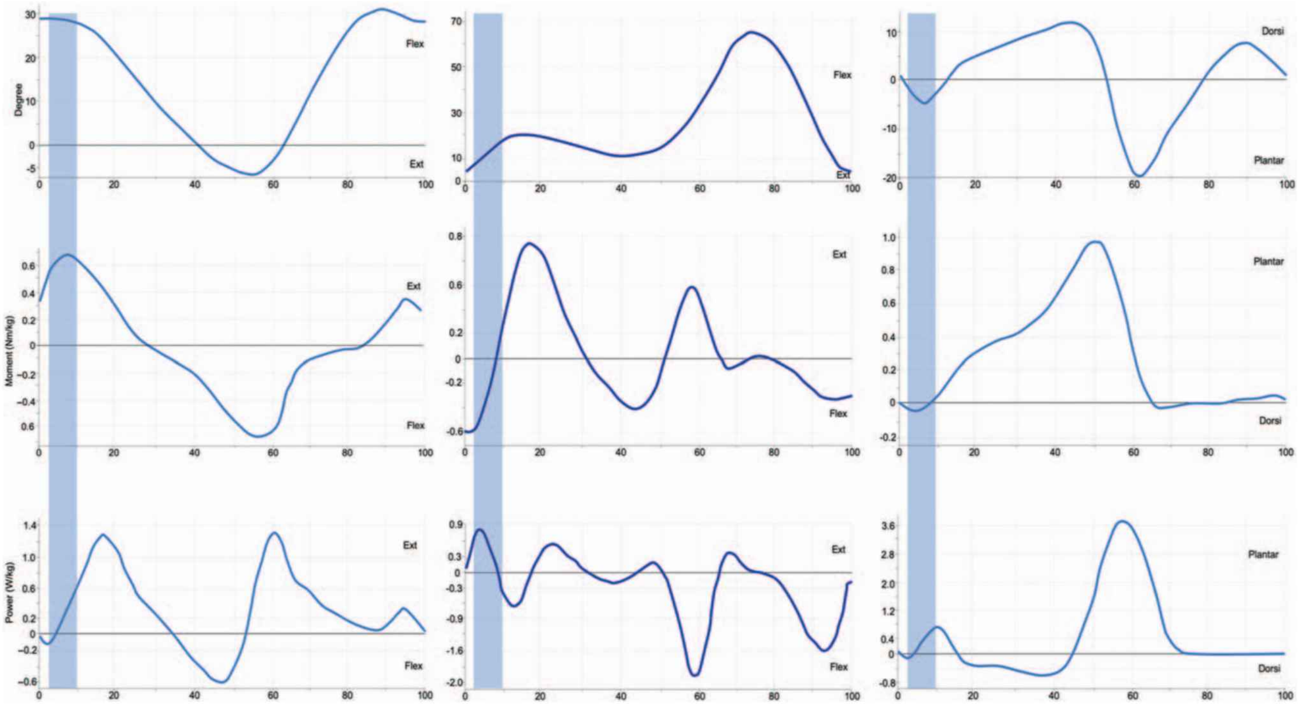


FIGURE 29.17 Kinetic attitude during the loading response. The blue area shows the related phase, the red line shows the moment at which the toe tips leave the ground.

stability. Unlike biceps femoris, medial hamstrings (semitendinosus and semimembranosus) contribute to the forward rotation of the opposite pelvis (Perry, 1992). In order to prevent the opposite pelvis from declining, gluteus medius and maximus as well as tensor fascia latae (26%–31% MMP) are eccentrically active (Perry, 1992). In this phase, the hip is in internal rotation. The reasons for this internal rotation are 1) ipsilateral (same side) subtalar joint eversion, 2) ipsilateral medial hamstring activation (medial hamstrings are also hip internal rotators), 3) recoil effect of the opposite plantar flexor muscles at the end of the stance phase. At this sub-phase, the knee abduction is high and the tension on the ilio-tibial band plays an important role in achieving lateral stability of the knee (Perry, 1992).

Mid-stance phase

Time period: 10%–30%

Task: Single limb support; to advance the body forward on a single foot in a specific order.

Critical aspect: controlling the forward movement of the tibia

Kinematics:

1. Hip from 30° to 0°
2. Knee from 15° to 0°
3. Ankle from a plantar flexion of 15° to a dorsiflexion of 10° (Fig. 29.18)

Active muscle group:

1. Soleus muscles are primarily composed of slowly contracting muscle fibers. They are contracted eccentrically to decrease angular speed of dorsiflexion during the second rocker movement and control the forward movement of the tibia.
2. Quadriceps stabilizes the knee in flexion. It ceased its function as the GRF passes in front of the knee.
3. Gluteus maximus ceases its activity once the GRF is passes to behind the hip joint.

This sub-phase is the first time period when only a single foot is on the ground. In other words, it is the time between the moment the opposite foot's toe tips leave the ground and the initial contact. During the mid-stance phase, the opposite foot is completely off the ground. The main goal of this sub-phase is to ensure a controlled forward movement and energy conservation. The first of key muscle group in this sub-phase is the plantar flexors. Soleus plays the leading role in controlling dorsiflexion. Soleus differs from the gastrocnemius by the fact that it is a plantar flexor, but not a knee flexor. During single limb stance, if the whole body is counted as a door mounted on the ground the hinge of the door attached to the ground would be the ankle joint. The soleus muscle would be a hydraulic door spring preventing the door from shutting down rapidly and allowing the whole body to move forward in a controlled way. This activity of the soleus muscle allows the GRF to move from back to front of the

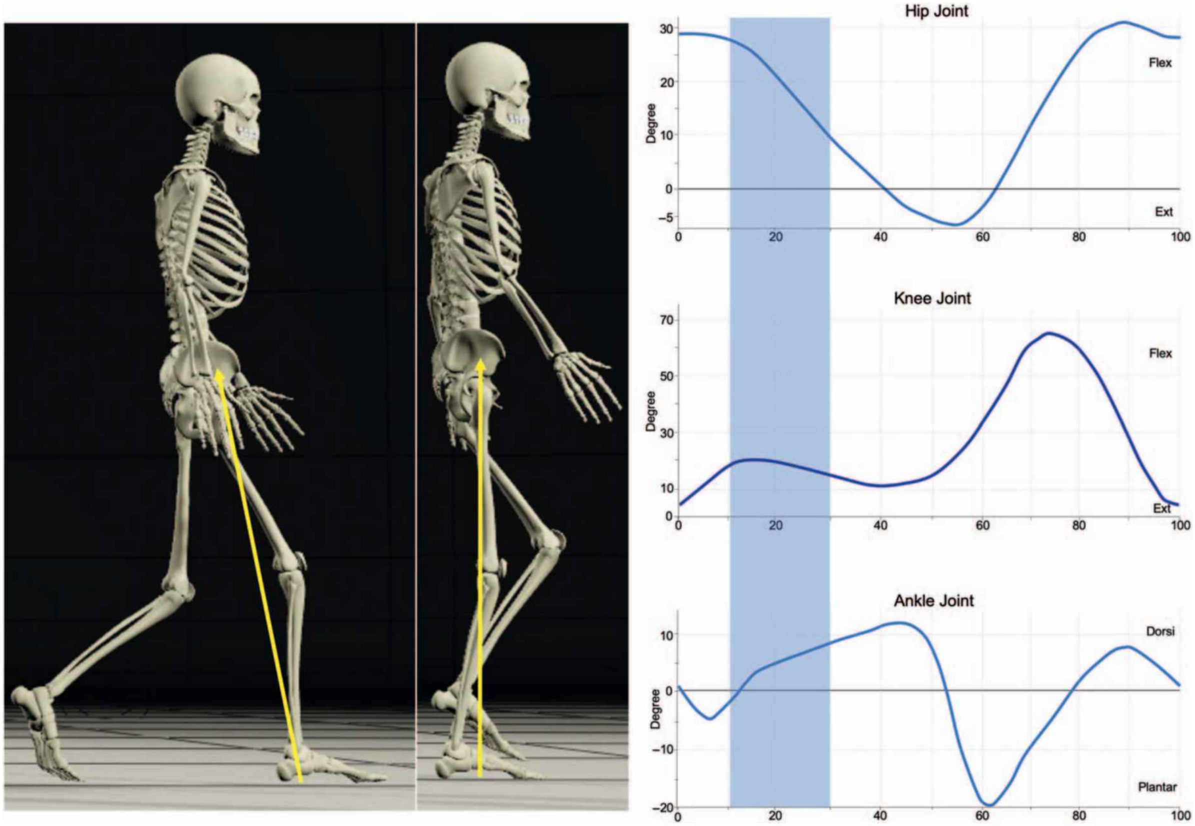


FIGURE 29.18 Mid-stance phase and its kinematic projection (from top to bottom, respectively, pelvis, hip, knee, and ankle, y: degree °, x: % gait cycle). The blue area shows the related sub-phase.

knee. Thus, the GRF helps the knee extension and increases the overall stability of whole lower extremity (Gage et al., 2009). This mechanism prevents the quadriceps from consuming energy by working as a knee extensor. Excessive knee extension is prevented by the posterior joint capsule. While the body moves forward with the ankle pivot, the GRF moves towards the back of the hip. This passive extension controlled by the iliofemoral ligament, therefore preventing the excessive hip extension does not need active hip flexors, that ensures energy conservation (Gage et al., 2009). The combined activity of the tibialis posterior and soleus prevents a hyper-pronation in the foot (Perry, 1992) (Fig. 29.19).

In this phase, the CoG reaches its highest point (Kauffmean and Sutherland, 2006). In the hip, the contraction of abductor muscles brings the hip to the neutral position in the coronal plane. Gluteus maximus and medius activities decrease while the tensor fascia latae activity starts (Perry, 1992). A slight vastus activity might occur at the beginning of this phase. This is only to ensure the start of knee extension; and it stops during 20% of the gait cycle. In the coronal plane, the abductor moment continues in the knee and the CoG moves by 2 cm towards the lateral line. However, the GRF is still on the medial compartment (at around 2.5 cm medial of the joint center). At this sub-phase, none of the muscles that give lateral support to the knee are active. Two important supporting structures in this phase are the tension on the iliotibial band (hip abductor activity) and the slight contraction of the lateral collateral ligament (Perry, 1992).

Terminal stance phase

Time period: 30%–50%

Task: Single limb support; the body moves ahead of the foot and the forward movement accelerates by means of concentric contraction of foot plantar flexors.

Critical aspect: Heel rise

Kinematics:

1. Hip from 0° to 10° hyper-extension
2. Knee flexion at 0°–5°
3. Ankle plantar flexion at 10°
4. Toes move from 0° to 30° hyper-extension (Fig. 29.20).

Active muscle group:

1. Soleus increases its activity to be able to limit the foot dorsiflexion. Also, during this stage, the

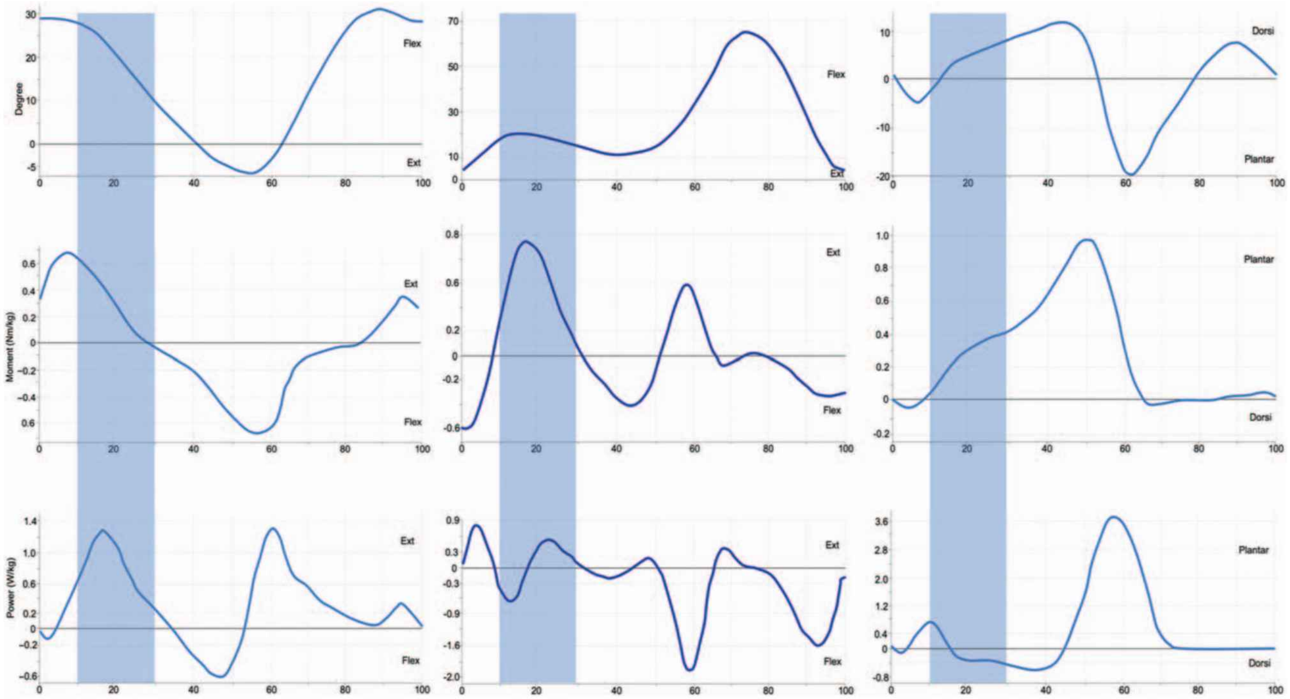


FIGURE 29.19 Kinetic attitude during the mid-stance phase. The blue area shows the related phase, the red line shows the moment at which the toe tips leave the ground.

subtalar joint begins invertion to lock the midtarsal joint, that it turns the foot to stiff lever arm required for propulsing the body forward.

2. Gastrocnemius primarily contains of fast twitch fibers. It prevents tibia from excessive forward movement over talus and brings the foot into plantar flexion. This activity creates the necessary power for the body to move forward. Gastrocnemius and the soleus meet 80% of the acceleration necessary for sustaining the gait.
3. Tibialis posterior acts as an inverting muscle in order to ensure the stabilization of the foot against the peroneal muscles.
4. Peroneal muscles also create the eversion power in order to provide stability against the foot invertors.
5. Long toe flexors, flexor hallucis longus and flexor digitorum longus muscles stabilize the metatarsophalangeal joints including toes as the load is transferred from mid-foot to forefoot.

The main goal of this sub-phase is to move the body forward. At this sub-phase, the activity of the plantar flexor muscles is very important. Toe flexors stop the ankle by joining the gastrocnemius and soleus (86% MMP) and make it move in the opposite direction (in the direction of the plantar flexion) with a concentric contraction (Gage et al., 2009). In this period, the plantar fascia is also passively contracted and helps achieve stability in the metatarsophalengeal joint (Perry, 1992). Peroneus longus activity helps the stabilization of 1st Ray (first row of the foot), which is subject to a high load during this phase. The slight inversion created by the plantar flexion locks the mid-tarsal joints and the "pivot" shifts from the ankle to metatarsal heads. that creates the highest plantar flexor force during the gait. Fast twitch fibers of the gastrocnemius, which take on the leading role at this phase, increases the angular speed of the ankle joint towards plantar flexion. This speed approaches to zero at the end of the stance phase. Knee flexion is around 5° at 39% of the gait cycle. At the end of this sub-phase, the knee flexion reaches 10°. The ground reaction force vector, which passes in the front of the knee, has a tendency to create a hyper-extension in the knee. However, the reaction to this tendency comes from the popliteus (14% MMP). Since the gastrocneimus is also a knee flexor, it protects the knee from hyper-extension. Moreover, the short head of the biceps femoris is also active at this sub-phase (21% MMP). The knee flexor moment is also high at this stage, but the joint power is variable depending on the gait speed. At the end of this phase, the tibia has a slight internal rotation because of the activity of the popliteus muscle (screw-home mechanism) to prepare the knee joint for the flexion. The hip extension continues by slowing down. A little iliopsoas activity may be observed (Kauffmean and Sutherland, 2006). However, the activity

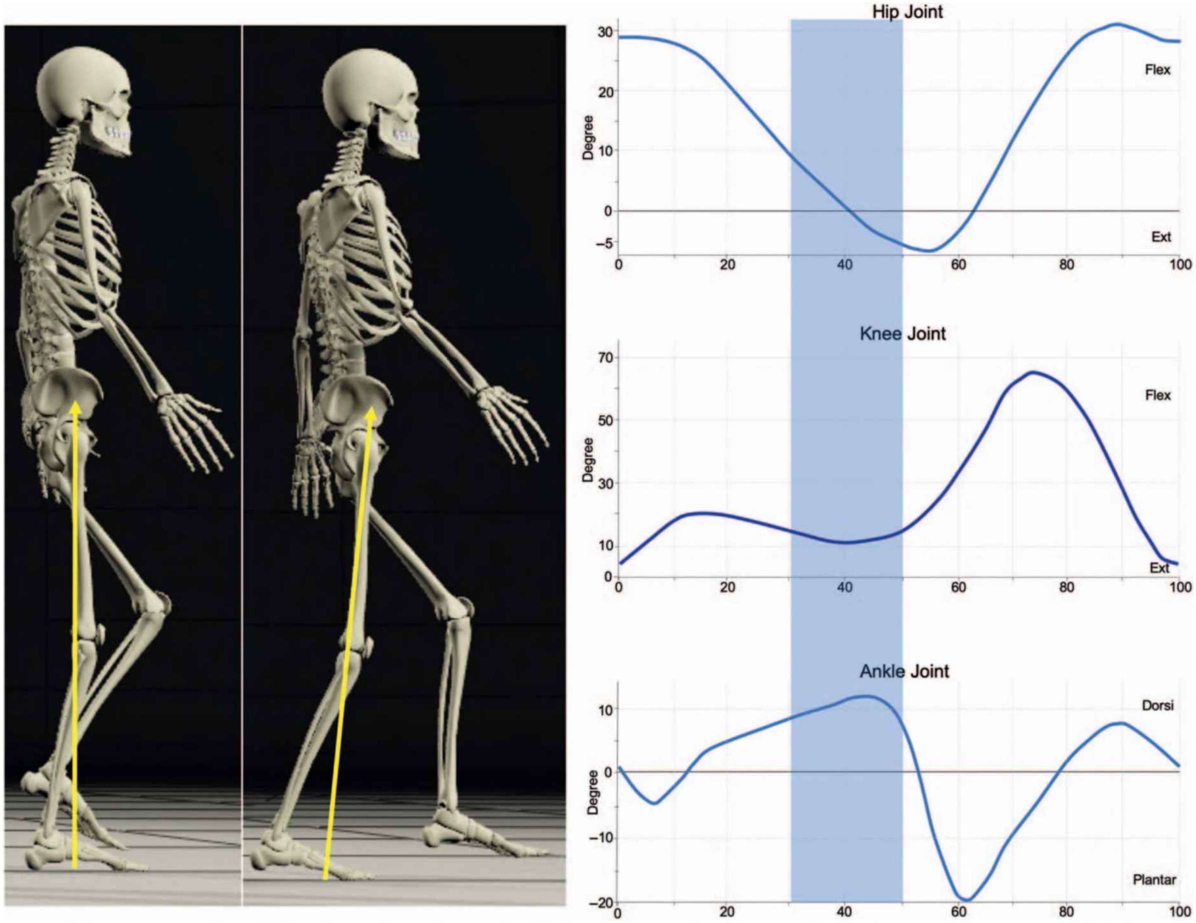


FIGURE 29.20 Terminal stance phase and its kinematic projection (from top to bottom, respectively, pelvis, hip, knee, and ankle, y: degree °, x: % gait cycle). The blue area shows the related sub-phase.

of the tensor fascia latae is significant and resists to extension as a hip flexor and it plays a role in achieving stability in the hip by means of the small hip abductor lever arm. At the end of this sub-phase, the adductor longus becomes active. As this muscle is also a hip flexor component, it prevents an increased hyper-extension of the hip. Pelvis achieves the highest degree of external rotation. This sub-phase is considered to be a preparation for the double-limb support phase (gait phase when both feet are on the ground) as the opposite leg comes end of the swing phase. At this sub-phase, tibialis anterior and posterior work together actively to provide medio-lateral stability in the foot. The stability of metatarsi is also important as the load shifts to the forefoot. This stability is ensured by the toe flexors (Gage et al., 2009). While the CoG shifts laterally over to the foot during the mid-stance phase, it changes direction towards the medial at this sub-phase. It facilitates the activity of hip abductors; however, their level of activity decreases as double support phase begins (Perry, 1992) (Fig. 29.21).

Pre-swing phase

Time period: 50%−60%

Task: To move the swinging leg forward, to prepare an appropriate position for the leg that is about to swing.

Critical aspect: Passive knee flexion

Kinematics:

1. Hip from a hyper-extension of 10° to 0°.
2. Knee flexion from 0° to 35°.
3. Ankle from 0° to a plantar flexion of 20° (Fig. 29.22).

Active muscle group:

1. Gastrocnemius prevents the knee from locking during this phase and releases the knee flexion.
2. While adductor longus muscle moves the femur forward and creates a moment of inertia on the tibia, passive flexion begins in the knee joint.
3. Rectus femoris muscle, which crosses two joints, is contracted eccentrically from its distal head to reduce the moment of inertia of the femur. Its

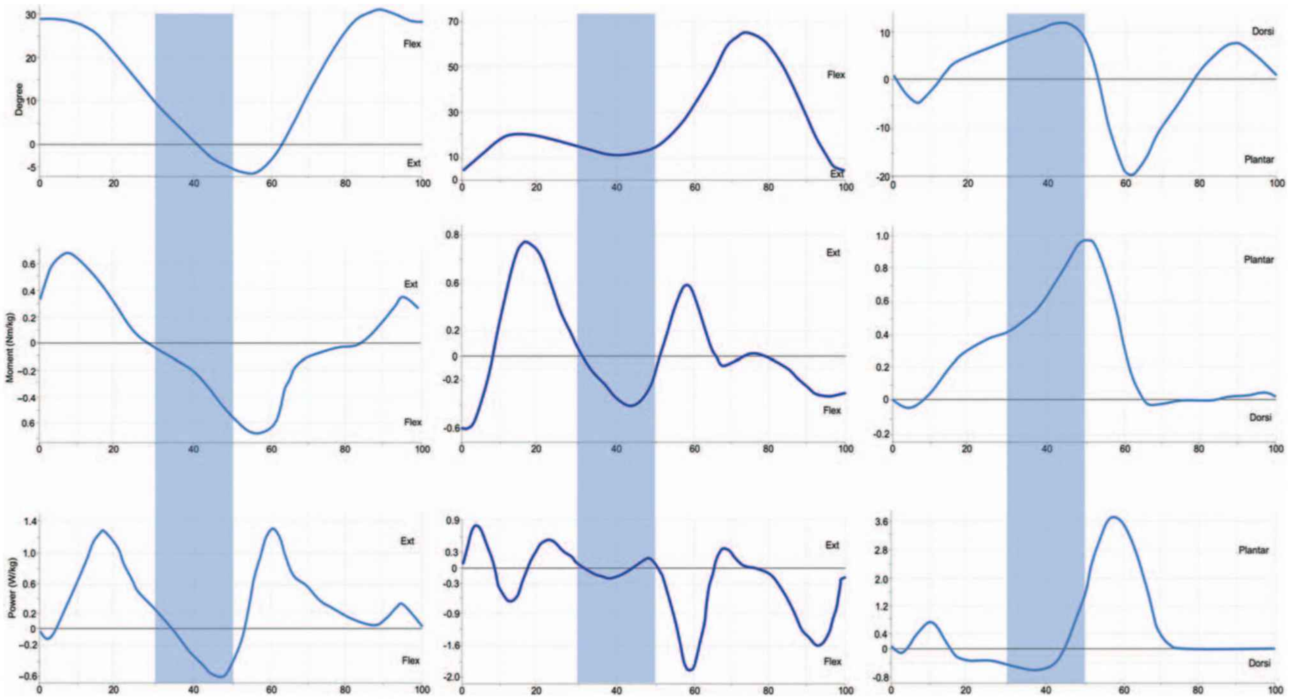


FIGURE 29.21 Kinetic attitude during the terminal stance phase. The blue area shows the related phase, the red line shows the moment at which the toe tips leave the ground.

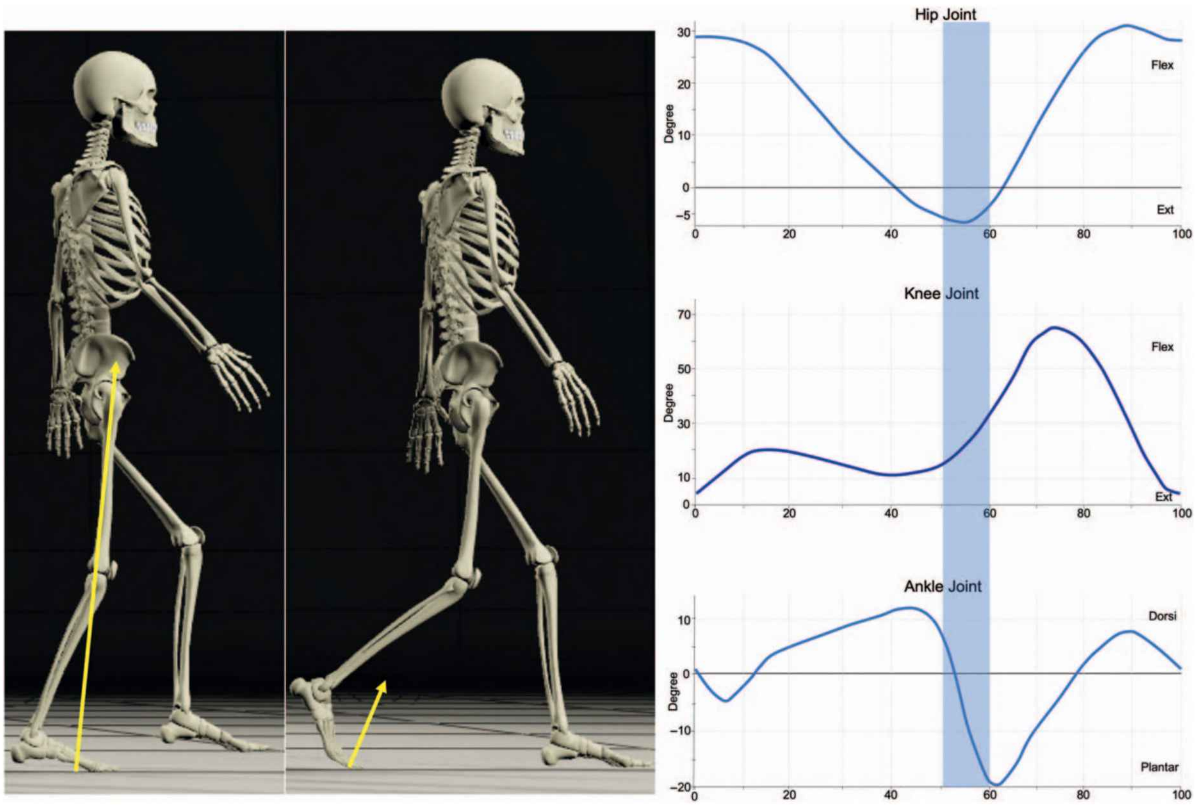


FIGURE 29.22 Pre-swing phase and its kinematic projection (from top to bottom, respectively, pelvis, hip, knee, and ankle, y: degree °, x: % gait cycle). The blue area shows the related sub-phase.

concentric contraction from its proximal head, on the other hand, increases the hip flexion. In this way, the energy is not wasted and transferred from the knee joint to the hip joint.

This sub-phase starts when the opposite foot contacts the ground. Thus, the second double-limb support period begins. The purpose of this period is to transfer the body weight to the opposite side and to prepare the leg for the swing. The GRF creates a high flexion moment at the knee as it passes through behind the knee joint. At this sub-phase, gastrocnemius and soleus muscles play a critical role in advancing the leg forward and upward directions. Despite their reduced activity at the end of this sub-phase, the plantar flexors still have a high moment, which is argued to be resulting from the recoil effect of the Achilles tendon (Fukunaga et al., 2001; Maganaris and Paul, 2002). This recoil effect causes 15° plantar flexion at the ankle joint. Additionally, the gastrocnemius, a part of the plantar flexor muscles also acts as a knee flexor (Fig. 29.23). Activity of tibialis anterior muscle starts at the pre-swing phase and it will play a significant role during the next sub-phase.

While hip flexors and adductors (adductor longus, brevis, gracilis) increase their activity and move hip joint towards flexion, the flexion moment and power at the hip joint significantly increase. At a normal gait speed, the rectus femoris shows a very slight activity. Hip flexors not only have a considerable effect on the hip but also on the knee flexion (Akalan et al., 2016a,b) in two ways. Distal end of the femur moves forward during hip flexion and creates inertia on the tibia, and stretched hamstrings increase the flexion moment at the knee joint. Thus, the knee flexion is reached to 40° at pre-swing phase, and 65° during the swing phase; thereby minimizing the risk of stumbling.

Initial swing phase

Time period: 60%–75%

Task: To advance the swinging leg forward, with various levels of potential acceleration.

Critical aspect: Moving the foot forward and achieving a sufficient flexion at the knee. At the initial swing, the forward movement speed of the tibia plays a significant role in achieving a sufficient level of flexion at the knee.

Kinematics:

1. Hip flexion from 0° to 20°
2. Knee flexion from 35° to 65°
3. Ankle plantar flexion from 10° to 0° (Fig. 29.24)

Active muscle group:

1. Hip flexor muscles (iliacus, adductor longus, sartorius, and gracilis) are activated in order to move the femur forward. Moreover, they help the femur to achieve moment of inertia to create a knee flexion.

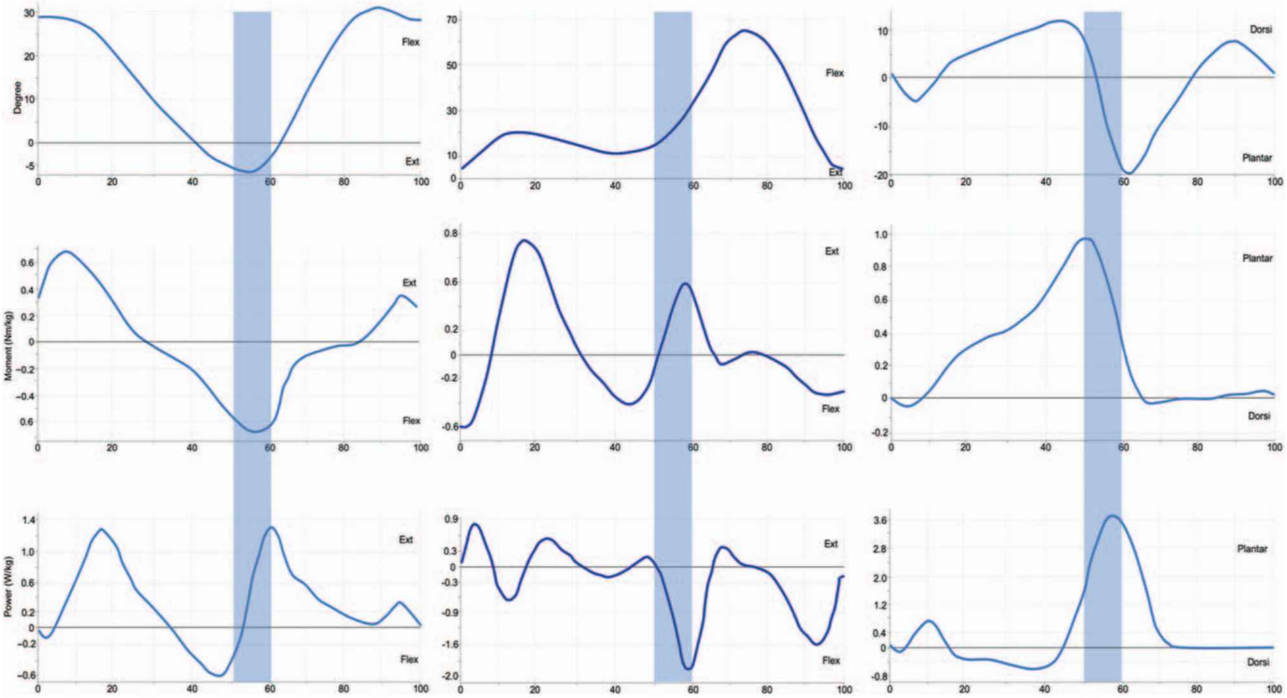


FIGURE 29.23 Kinetic attitude during the pre-swing phase. The blue area shows the related phase, the red line shows the moment at which the toe tips leave the ground.

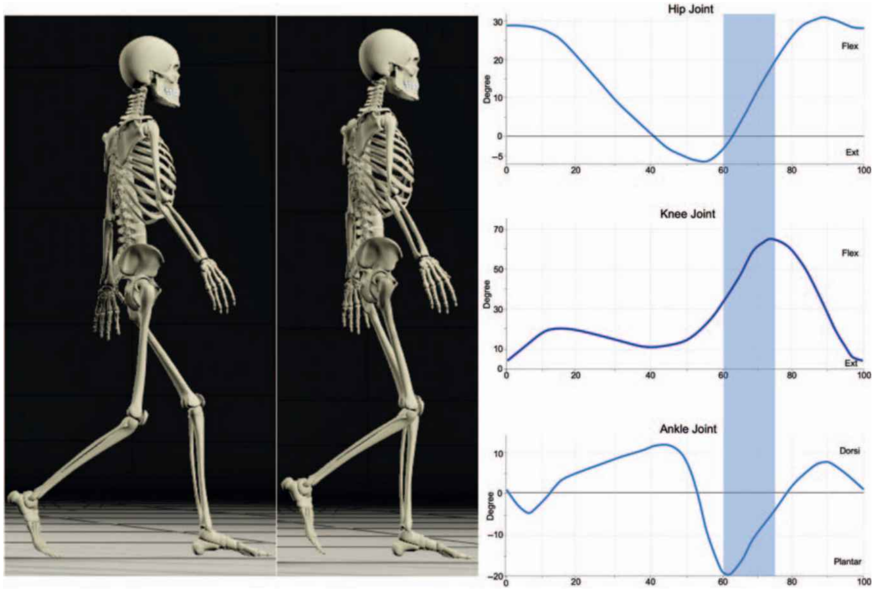


FIGURE 29.24 Initial swing phase and its kinematic projection (from top to bottom, respectively, pelvis, hip, knee, and ankle, y: degree °, x: % gait cycle). The blue area shows the related sub-phase.

2. Biceps femoris (short head) is activated to increase the knee flexion particularly during the slow gait when the moment of inertia is not sufficient.
3. Tibialis anterior and long toe extensors are contracted concentrically to move the ankle joint into dorsiflexion.

Initial swing starts with the elevation of the toe tips from the ground and continues until the moment when the same foot comes near to the supporting leg. This phase aims to move the leg forward in a completely passive way (passive pendulum) without any observed muscle activity, with the exception of the elevation of the frontal part of the foot by means of the tibialis anterior and toe extensors. As gait speed and required muscle activity may differ from one to other individuals each individual has his /her own optimum gait speed as well as other gait variables to keep the energy expenditure in minimum.

During the initial swing, plantar flexion at the ankle joint decreases from 15° to 5° because of the dorsiflexors (25% MMP). As the tibia approaches a vertical position, toe extensors will have a higher level of activation (extensor digitorum longus: 32% MMP, extensor hallucis longus: 40% MMP) and in particular, the first toe extension becomes visible (Perry, 1992) (Fig. 29.25). The swinging (ipsilateral) leg is relatively longer than the leg (contralateral) at the stance phase. Therefore, the swinging leg should be shortened with an additional knee flexion. In conditions where this knee flexion is required (uneven surface, stumbling moment, etc.), the short head of the biceps femoris, sartorius, and gracilis reach 20% MMP and increase the knee and hip flexions (Perry, 1992).

Mid-swing phase

Time period: 75%–90%

Task: Advancing the swinging leg forward

Critical aspect: Vertical position of the tibia; advancing the foot forward

Kinematics:
1. Hip flexion from 20° 30°
2. Knee flexion from 60° to 30°
3. Ankle plantar flexion from 10° to 0° (Fig. 29.26)

Active muscle group:
1. Tibialis anterior muscle provide the neutral position of the ankle and prevent the foot drop.

The main goal of mid-stance is to ensure a transition between the start and the end of the swing phase without scraping the ground with the toe tips. The tibialis anterior remains active. Passive pendulum motion continues. In this way, ankle dorsiflexion slightly increases. The pre-tibial muscle shows isometric activity in this phase (Fig. 29.27).

Terminal swing phase

Time period: 90%–100%

Task: Advancing the swinging leg forward, achieving the maximum step length, slowing down the swinging leg and ensuring an appropriate position for the foot contact with the ground.

Critical aspect: Knee extension until neutral (Davis, 1996).

Kinematics:
1. Hip flexion 30°
2. Knee flexion from 30° to 0°
3. Ankle at 0° (6) (Fig. 29.28).

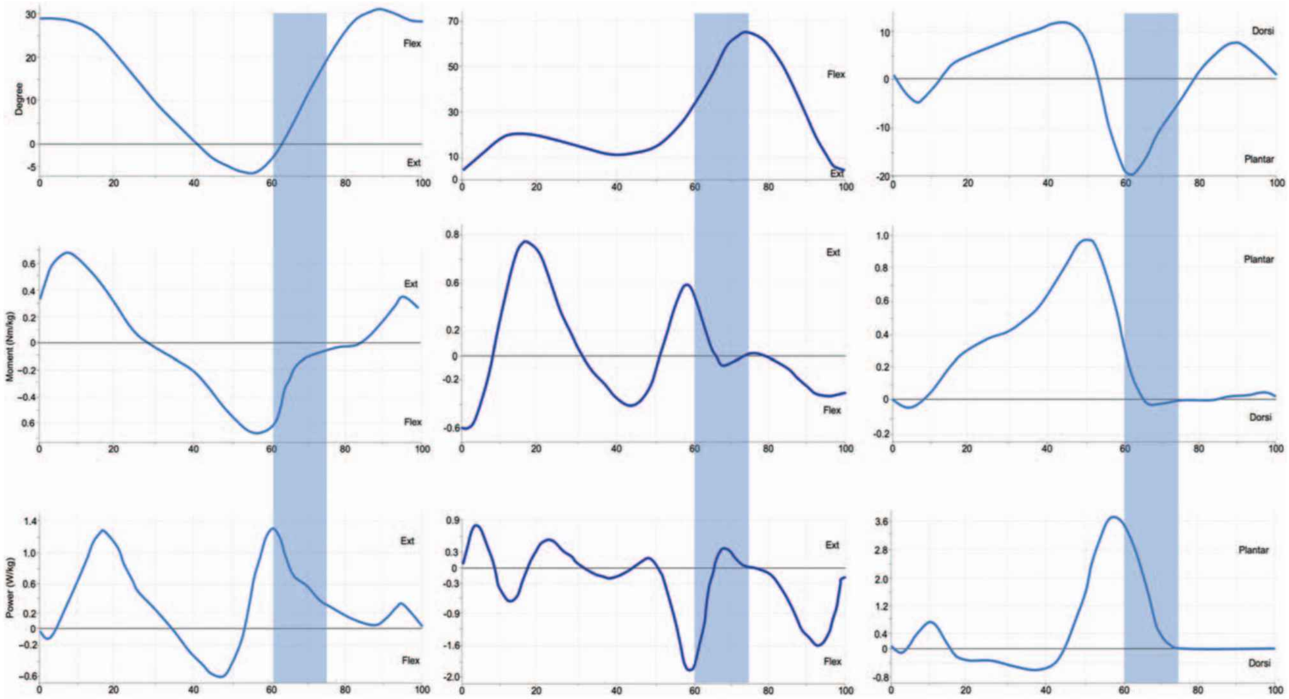


FIGURE 29.25 Kinetic attitude during the initial swing phase. The blue area shows the related phase, the red line shows the moment at which the toe tips leave the ground.

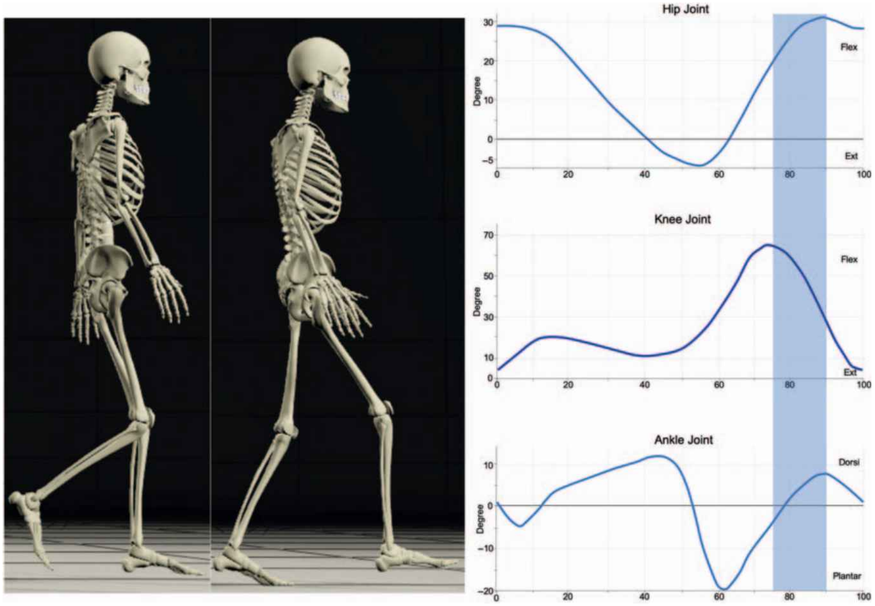


FIGURE 29.26 Mid-swing phase and its kinematic projection (from top to bottom, respectively, pelvis, hip, knee, and ankle, y: degree °, x: % gait cycle). The blue area shows the related sub-phase.

Active muscle group:

1. Hamstrings slow down the forward movement of the femur and the leg by affecting the knee and the hip.
2. Quadriceps provide knee extension for the stance phase.
3. Tibialis anterior stabilizes the ankle by causing a dorsiflexion and creates an appropriate position for the foot contact with the ground (Gage, 1991).

Terminal swing aims to prepare the swinging leg for the stance phase. The ankle achieves the dorsiflexion required for the heel strike. As for the knee joint, flexion at the beginning of the swing phase must be reversed. Hip extensors (gluteus maximus and adductor magnus) including the hamstrings slow down the forward movement of the femur and create moment of inertia on the tibia, the eccentric contraction of the hamstrings allows the lower

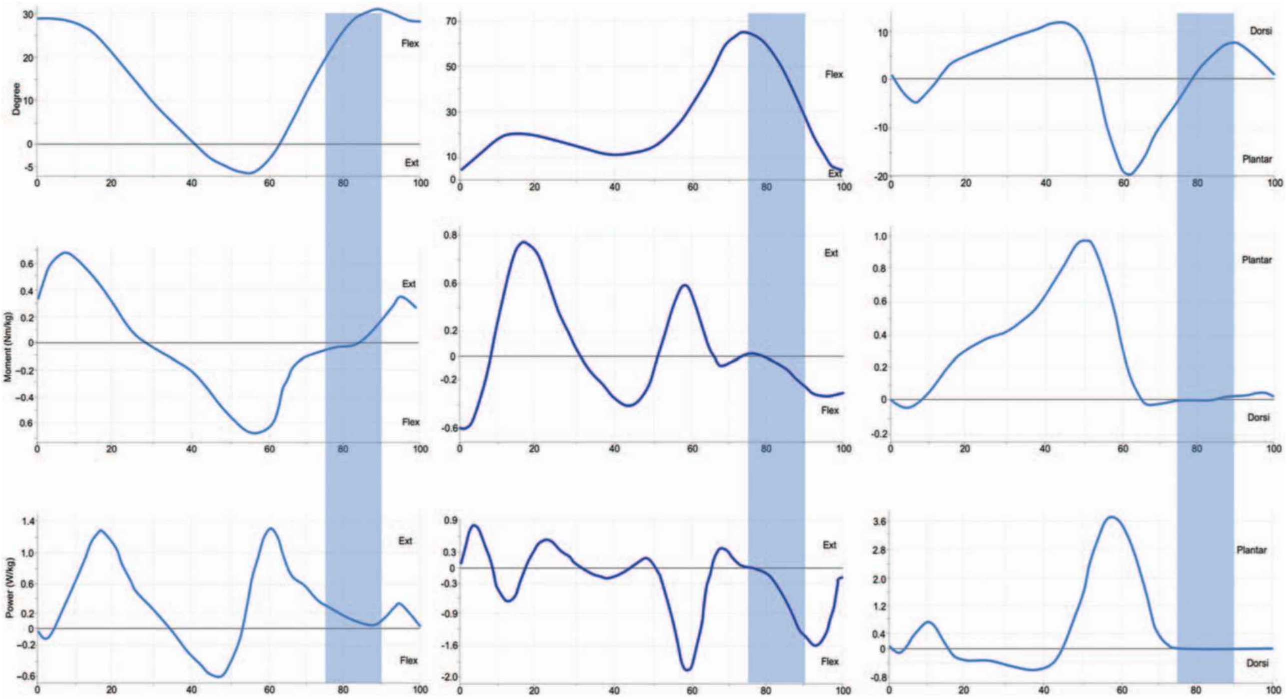


FIGURE 29.27 Kinetic attitude during the mid-swing phase. The blue area shows the related phase, the red line shows the moment at which the toe tips leave the ground.

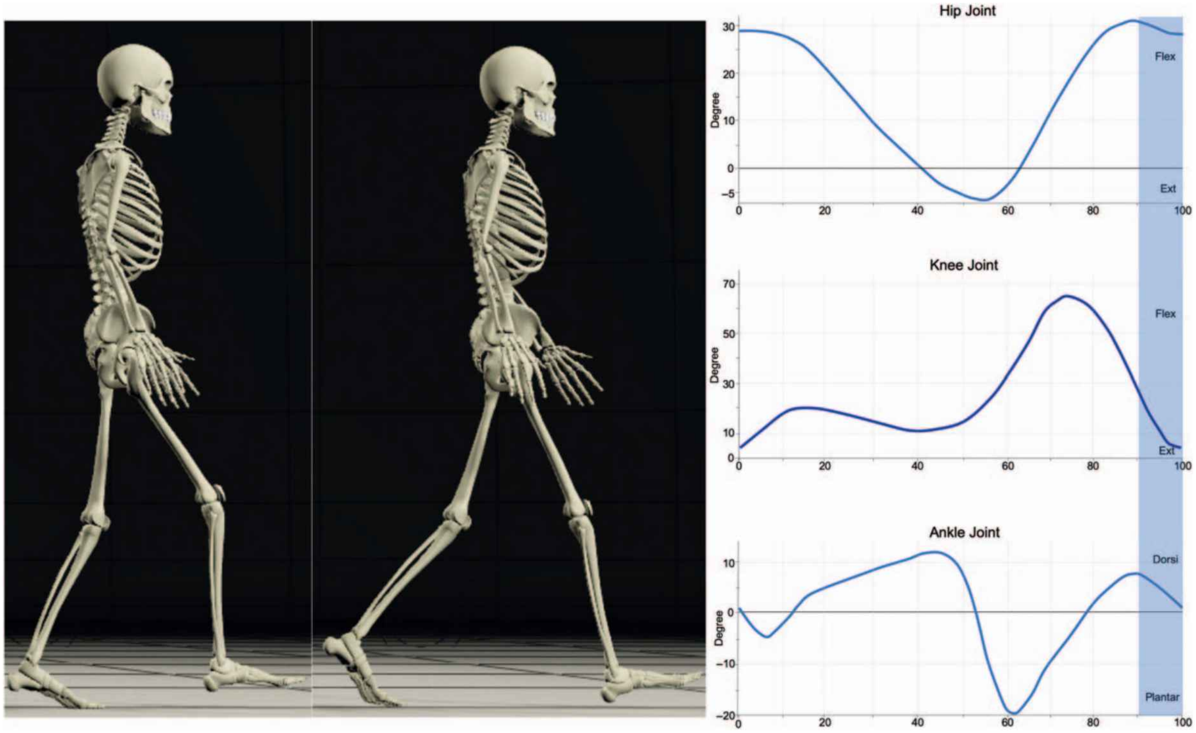


FIGURE 29.28 Terminal swing phase and its kinematic projection. The blue area shows the related sub-phase.

leg to move forward with the help of the inertial moment of the tibia. In other words, hamstring muscles act as a knee extensor while slowing down the hip flexion. Because, the moment arm of hamstrings at the knee joint is half of the length of the moment arms at the hip joint. Therefore, the moment produced by the hamstring

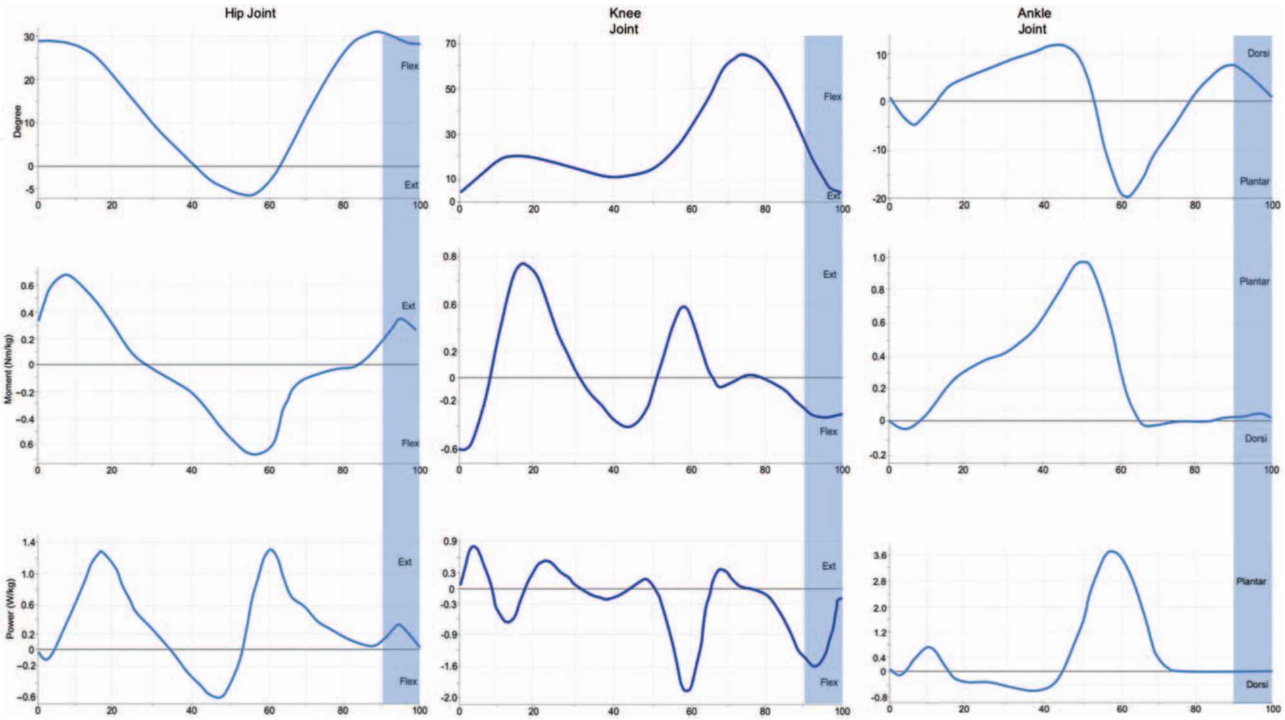


FIGURE 29.29 Kinetic attitude during the terminal swing phase. The blue area shows the related phase, the red line shows the moment at which the toe tips leave the ground.

muscles at the knee joint is nearly half of the moment created at the hip joint. In this way, the lower leg continues to move forward irrespective of the slower forward movement of the femur (pendulum effect), thus the knee achieves its extended position.

At the terminal swing, the vastus is activated only for protection purposes so as to prevent the collapse of the knee in case of an unexpected initial contact (Perry, 1992). Gluteus medius may be active only if the hip adduction increases. During this sub-phase, rectus femoris activity is not required because the hip flexion is not desired at this phase (Fig. 29.29).

As a result, the gait is a collection of highly complex motions that are difficult to understand, yet play a critical role in everyday life. In this section, the fundamental aspects of the normal gait and its sub-phases are described. We should be able to understand the normal gait characteristics must be understood in order to understand the pathological gait. A thorough comprehension of the normal gait is crucial to identify the primary, secondary, and tertiary problems that manifest in the pathological gait.

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Chapter 30

Biomechanical principles of the exercise design

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Introduction

From the perspective of the evidence-based medicine, the exercise therapy is the best available active treatment method for several neuro-musculo-skeletal disorders (Smidt et al., 2005; White et al., 2011; Swart et al., 2016; Bartholdy et al., 2017; da Silva Rosa et al., 2017; New et al., 2017; Sandler et al., 2017). The human body is tend to get better at what it performing regularly (Eisner, 2017). So that when the human body is stressed under some form of loading, that will lead adaptations; thus, it will allow the human body to get a better state that the specific form of biological stress in the future. Therefore, the exercise design is important for everyone and for individuals with the specific demands and the applying the biomechanical principles simply changes stress in any particular exercise. The wide variety of exercise movements carried out by the human musculoskeletal system are all performed by the same elements: muscles, bones, joints, and the nervous system including receptors (Brewer, 2017). Biomechanics can be defined as the application of the physics to the movement, and can be accepted as an one of the important field for studying body movement and performance (van Keeken et al., 2016). From this point of view, the exercise movements can be assessed through biomechanical principles. This chapter includes, application of the biomechanical principles combined with neuromuscular efficiency, neural adaptation, proprioceptive demands and optimal neuromuscular control for exercise design.

Basic principles of exercise

Through its basic principles, exercise movement can be progressed easily to adapt to the patient's condition and to create targeted physiological effects.

Individuality: Optimal benefits occur when exercise meet the individuals needs and capacities of the patient or client. The exercise prescription should be based on individual needs that will change by person to person.

Trainability: It is another principle that explains each person responds differently to the same training stimulus.

Specificity: The training stimulus must be specific to the patient or clients desired outcomes. Therefore, exercise design must be specific to individuals' goals.

Overload: It is important to consider that for adaptation to occur the volume of exercise must overload the body in some way in line with the capacity of the individual to cope with that overload.

Progressive Overload: For continual adaptation overload must be progressive, that is the dose of loading or stress must increase.

Variability: It should be kept in mind that for optimal adaptation and to avoid stagnation, overuse, and injury the exercise stimulus must be varied. Therefore, variety allows recovery and can reduce injury risk.

Rest: Optimal adaptation requires sufficient rest periods to be interspersed with training sessions that the adaptations caused by the exercise dose can take place.

Reversibility: All beneficial effects of exercise training are reversible if exercise ceases.

Overall, each of the exercise components has an ideal training frequency, intensity, time and type of exercise (FITT) to be used. The FITT principle is largely a practical integration of all the other exercise principles

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Mechanical basis of exercise design

Basic concepts of biomechanics in exercise design

Biomechanics is a scientific discipline including the mechanical principles and equations to understand how the human body functions in a wide spectrum of movements and exercise activities (Winter, 2009). However, this approach has often been criticized since like any other scientific discipline, the biomechanical principles of the exercise design have limitations of the paradigms, which regard the human body as a physical machine (Raikova, 1999; Siff, 2000; Dudley, 2002; van Keeken et al., 2016). Biomechanics should be applied to exercise training and sports within an integrated framework comprising all possible fields which relate to the structure and function of the human body.

Force

When force applied to an object, the object starts to move, stop, speed up, slow down, or change direction of the movement. That is explained in 1st. rule of Newton. Since the force is a vectoral quantity, it needs specification of direction, velocity, acceleration, force and moment. During resistive exercise training, if applied force is changed in amount, the intensity of the exercise alters. The direction of the force affects the activated muscle groups.

Velocity

The velocity V is the rate of change in position of a moving object with respect to time (m s^{-1}). Hill described the dependence of force on velocity of movement for isolated muscle with very best known hyperbolic curve in 1953 (Fig. 30.1; Gülch, 1994). Later studies (Zatsiorsky and Matveev, 1964; Komi and Tesch, 1979) also confirmed the relationship between velocity and exerted force during the complex sportive activities. The force–velocity curve presents that the velocity of muscular contraction is inversely proportional to the loading indicating that larger forces cannot be exerted in very rapid movements and the greatest velocities are attained under conditions of low loading. In Fig. 30.1, the area under the curve represents power which equals to force × velocity. Increase in strength changes curve profile, which means power is increased at all points on the curve. Previously, the effect of heavy strength training has been shown to shift the curve upwards (Perrine and Edgerton, 1977; Caiozzo et al., 1981; Lamb, 1984), Velocity is important when considering ballistic exercises such as plyometrics. It has been shown that light, high-velocity training shifts the maximum of the velocity curve to the right (Zatsiorsky, 1995).

Work

Work is the product of force and the amount of displacement (Harman, 1993). The Joule is the unit of work equal to the work done by a force of one newton when its point of application moves one meter in the direction of action of the force, equivalent to one 3600th of a watt-hour.

Movement planes

The universal method for defining movements is based on the plane and the axes system (Fig. 30.2). A plane is a flat, two-dimensional virtual surface. There are three cardinal planes that intersecting at the center of gravity of the human body (Fig. 30.3). Anatomical point of view, a movement may be parallel to one of these planes, moving segment rotates around an axis which perpendicular to the plane.

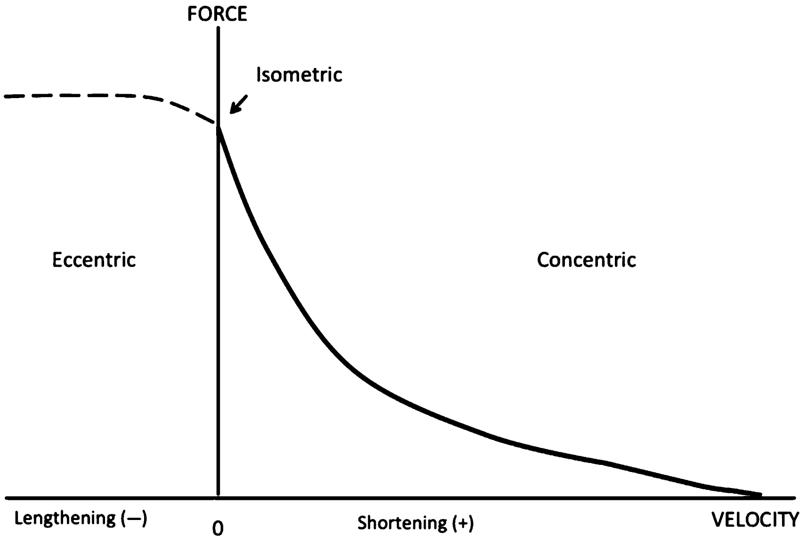


FIGURE 30.1 The Force–velocity relationship of muscle.

The exercise movements can be described based on the corresponding motion planes. For example, sit ups exercise is one of the exercise that targets anterior myofascial chains with focus on rectus abdominis muscle, which contains movement on the sagittal plane (Fig. 30.4) (Whiting et al., 1999). The sagittal plane movements are best viewed from the lateral side of the body.

Sling based hip abduction exercise can be given as an example of exercise movement in the frontal plane (Fig. 30.5). During this exercise hip abduction is performed in closed kinetic chain movement form with using ropes and slings. The successful exercise is performed while maintaining upright body position. The optimal position to observe frontal plane movements is from anterior or posterior side of the human body.

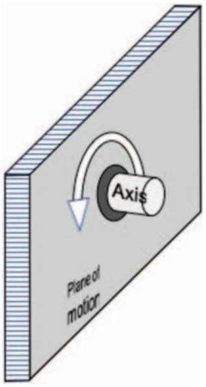


FIGURE 30.2 The plane and the axis.

The forearm supination-pronation exercise is an example of an exercise in the transvers plane, a simple anatomic motion on the transvers plane. (Fig. 30.6).

In the kinetic chain approach, exercise movements may occur include on multiple planes in the different joints. During the lawnmower exercise, for example, the lower extremity appears to move on the sagittal plane as the knees and the hips moving into flexion-extension (Fig. 30.7) while the torso rotates on the transvers plane.

Degree of freedom in exercise

The degree of freedom (DF) term may be used to describe any exercise movement in a corresponding plane. However, these terms are widely used to define the amount of motion structurally allowed by the joints. If a joint with 1 DF, the joint allows the segment to move on one motion plane. For example, the elbow joint moves only flexion-extension in the sagittal plane.

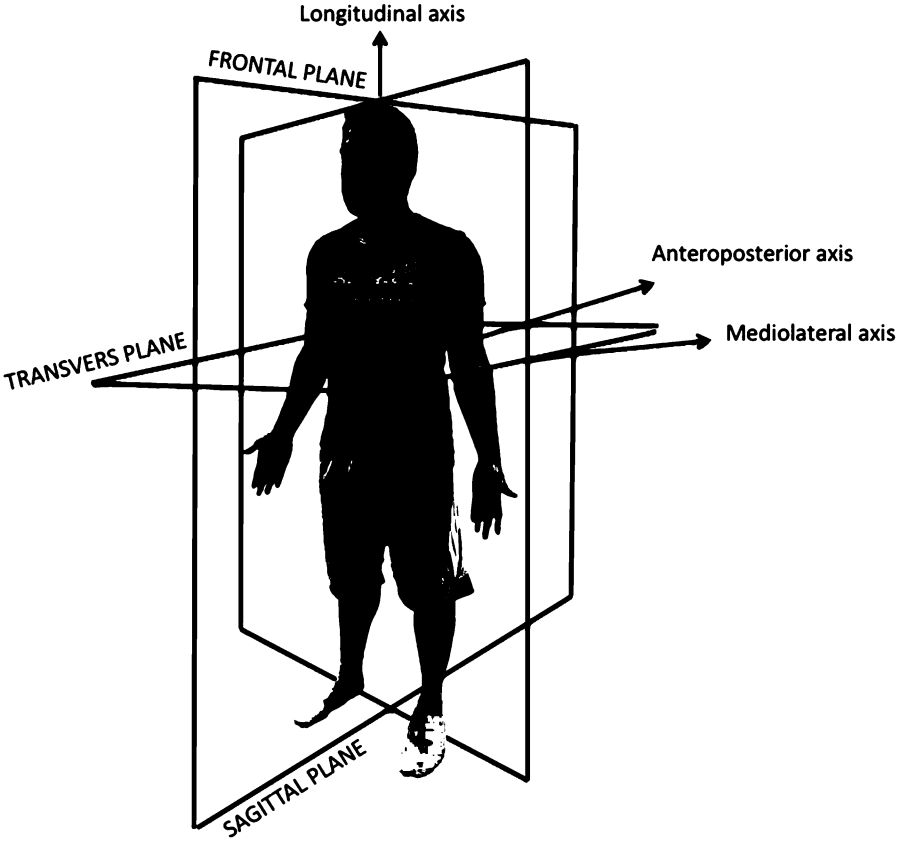


FIGURE 30.3 Planes and axes of the human body.

FIGURE 30.4 The sit-ups exercise.

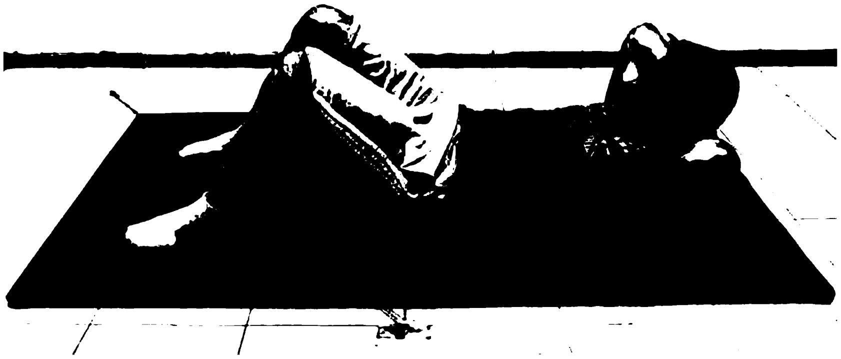


FIGURE 30.5 Side lying hip abduction exercise.

FIGURE 30.6 Forearm supination-pronation exercise.

FIGURE 30.7 The lawnmower exercise.

Also, gliding and/or roll motions may occur across the joint surfaces (Norkin and White, 2016). These motions may be interpreted as adding to more degrees of freedom to joints., A kinematic chain that is derived from combination of degrees of freedom at various joints produces exercise movements. The chain is summation of the DF in related joints that shows the total DF available or necessary for a targeted exercise movement. For instance, overhead throwing might involve a 12-DF system relative to the trunk. This would include perhaps 3 DF at the shoulder, 2 DF at the elbow, 2 DF at the wrist, 3 DF in the carpal bones, and 2 DF in the fingers (Hamill and Knutzen, 2006).

Fundamental concepts of mechanics in exercise design

Mechanics is a quantitative science provides the description of the human movement in a quantitative manner (Winter, 2009). All movement of the human body can be explained by the lever systems. Therefore, for any exercise setup, created moments by lever systems may guide to unload or load to change intensity of the exercise.

A lever is a rigid bar that moves on a fulcrum, when a force is applied to it (Fig. 30.8). The levers can be classified into as first class lever, second-class lever, and third class lever. In the human body, the bones represent the lever arm and joints represent the fulcrum. There are three forces in a lever system:

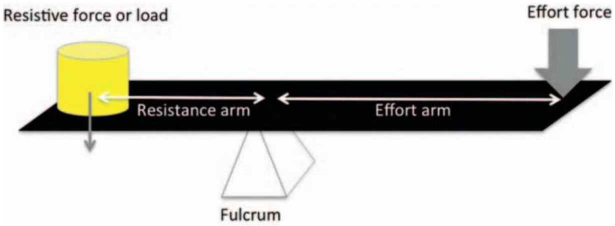


FIGURE 30.8 A lever system.

Effort Force: The effort force tends to create the desired movement. For the human body, the muscle activity exerted the effort force. The distance from the axis to the effort force is called effort arm.

Resistive Force: The resistive force tends to oppose the desired movement. For the human body the weight of a body segment or an external weight is the resistive force. The resistance arm is defined as a distance from the motion axis to the resistive force.

The force on axis (fulcrum): The force that equalize the resultant torque created by effort force and resistive force.

Torque is defined as the rotational effect of force explained as force (N) x moment arm (m) and represented as Nm. Throughout exercise movements, the torque differs in joints. In any lever system, mechanical advantage could either be in a favor of the effort force or the resistive force. This depends on the ratio of effort arm to resistance arm (García-Morales et al., 2003). If this ratio > 1, the effort force is greater than the resistive force. On the other hand, if the ratio <1, the effort force is less than the resistive force. When considering the types of muscular contraction, a concentric muscular action occurs when the produced muscular force is greater than the resistance, therefore as in the biceps curl exercise, the biceps brachii shortens. On the other hand, an eccentric action occurs when the force generated by the muscle is less than the resistance, so the muscle actively lengthens.

Because of their fundamental importance, implications of the exercise mechanics may be explained by Newton's Laws of Motion. For example, according to Newton's third law (Law of Reaction), when force applied to a stabile object creates an equal and opposite reaction force. This means that when two objects exert a force on each other and if objects are not in the move the forces are equal in magnitude and opposite in direction. During wall press exercise performed with balance disc, there is an equal and opposite reaction force occurs between upper extremity and the wall through disc (Fig. 30.9).

Balance is an important variable for assessing human neuromuscular function. From the mechanical perspective, an object is in static equilibrium when the resultant force or moment is equal to zero. If the forces and moments do not add up to zero, the object would not be in static equilibrium and it would move considering Newton's second law, the object would accelerate as well.

Center of gravity (CoG) is the virtual point in a body or an object around which it's mass or weight is evenly distributed or balanced, and through which the force of gravity acts. The CoG is a useful concept for analysis of human movement because it is the point at which the entire mass or weight of the body may be considered to be concentrated. Therefore, the force of gravity acts downward through this point to the surface. For human body, standing in the anatomical position, CoG lies approximately slightly anterior to the second sacral vertebral body (Palmer, 1944). This point always changes since the human body moves and does not remain fixed in the anatomical position during daily life and exercising. The location of the CoG changes constantly with every unique position of the body and limbs. The exercise specifications may change when the distance between segmental CoG and the common CoG is changed. For example, during sit-ups exercise, abdominal muscles may work harder in arm flexed position than in arm extended by side because the location of CoG move proximally and increase resistance to the abdominal muscles. The anthropometric characteristics of the individuals also affect the location of the CoG in nature (Hasan et al., 1996). Another terms such as stability often used while explaining balance or capability of body that returning to previous position after a perturbation. Apparently, the stability of a human body is affected by the factors such as the height of the CoG, the size of the base of support, and the weight of the body. The base of support is the area within the boundaries connecting each points of support. Different exercise set ups can be used for creating various base of support area; thus, increase the level of challenge for the neuromuscular system. Fig. 30.10 shows examples of various exercise positions with different bases of support area.

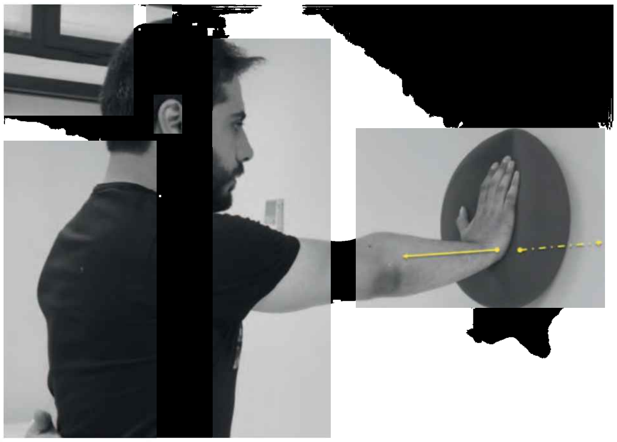


FIGURE 30.9 Wall press exercise.

Movement is described as a change in place, position, or posture occurring over time or relative to any point in the space. There are two types of motion are presented. Firstly, The motion may be linear, in which all points on a body or an object move the same distance and direction in the same amount of time. The pathway either can be straight (rectilinear) or curved (curvilinear) such as trajectory of a thrown ball. The common idea behind the activity with linear motion is that activity occurs on a particular direction, follows a path. The linear motion can be easily analyzed by the observing the motion of the center of mass of an object. For human body, it is also possible to analyze the center of mass or any selected point of a body segment for linear motion analysis. All linear motion during daily life activities and sports performance occur as a result of angular contributions of the body segments through joints. At the joint, angular motion of the relevant body segment occurs around an imaginary line called the axis of the motion. During angular motion, the body segment do not move through the same distance and direction in a specific time duration. For example, swinging of a gymnast on the bar is an angular motion.

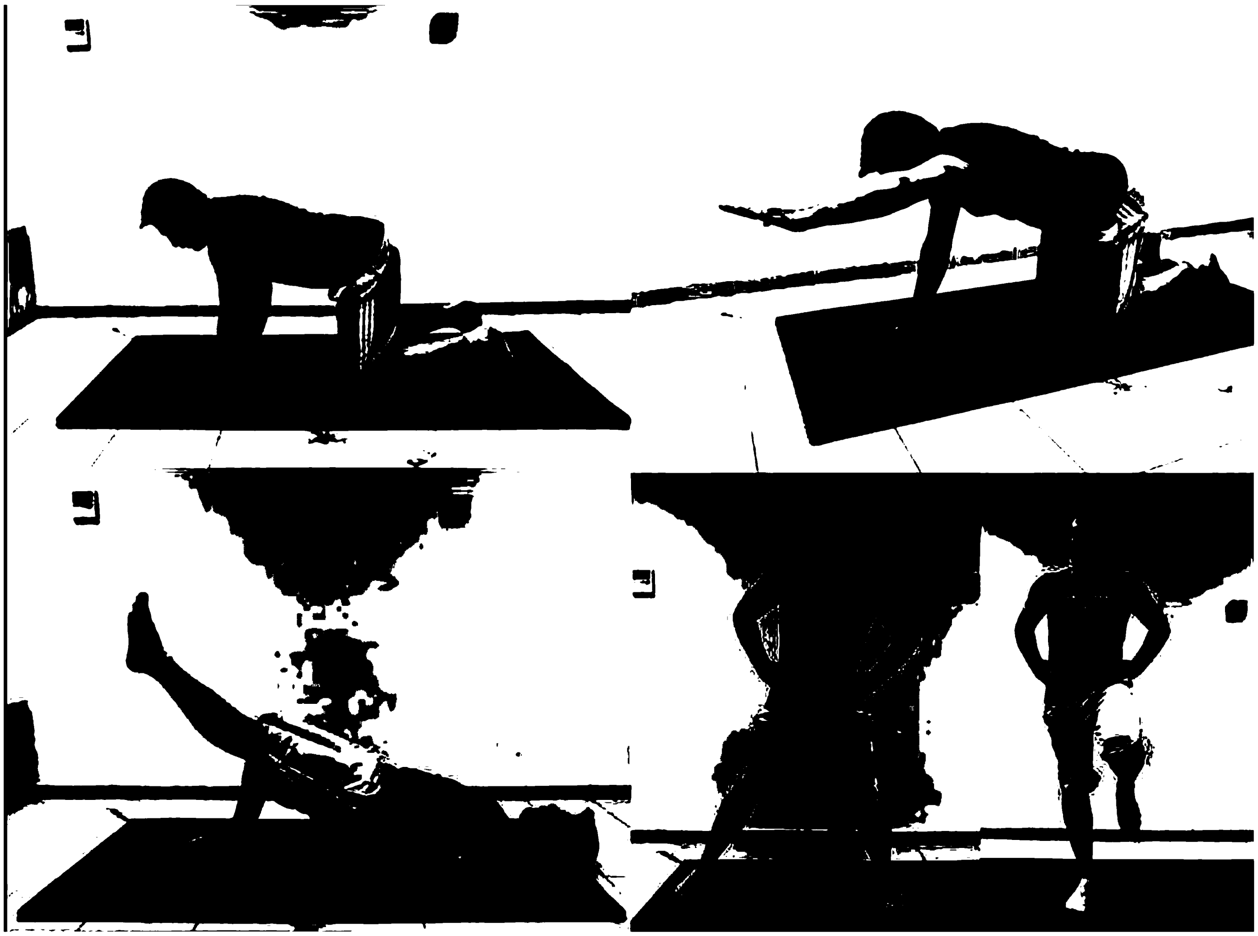


FIGURE 30.10 Base of support area in different exercise set-ups.

Identifying the type of motion in a particular exercise helps to mechanically analyze the exercise.

The biomechanical analysis of any exercise movement can be performed using kinematics and kinetics. The kinematics is concerned with the spatial and temporal characteristics of exercise movement without reference to the forces causing the motion. Kinematic analysis can provide information about position, velocity, and acceleration such as speed of body segment during jumping or degree of scapular rotation during shoulder elevation exercise. Fig. 30.11 represents three-dimensional scapular kinematics during humero-thoracic elevation. The movement occurs on the clavicle, scapula, and humerus. The coupled rotations in the sternoclavicular and acromioclavicular joints are result in scapular movements and it depends on factors such as thoracic posture, amount and direction of resultant force exerted by muscles, condition of acromioclavicular and sternoclavicular joints (Ludewig and Reynolds, 2009).

Kinetics examines the forces acting on the human body. A force that creates movement or provide equilibrium against external forces can be measured by specific instruments such as forceplates, accelerometers and EMG. The external and internal forces acting on the human body and by human body (internal forces) can be calculated according to its segmental position in a given time and obtained kinematic data of that pre-defined motion. This inverse dynamic procedure widely used for movement analysis. Therefore, a kinetic analysis can provide information about movement quality, harmony within the involved muscles in specific duration which the movement required. This would also provide base information for exercise design in training and rehabilitation.

Internal biomechanics

The any exercise movements are determined by the external forces acting on the body segments. These forces always create internal forces for moving the body part against the external force or equalize the external force to keep body segment still. Forces on the body segments

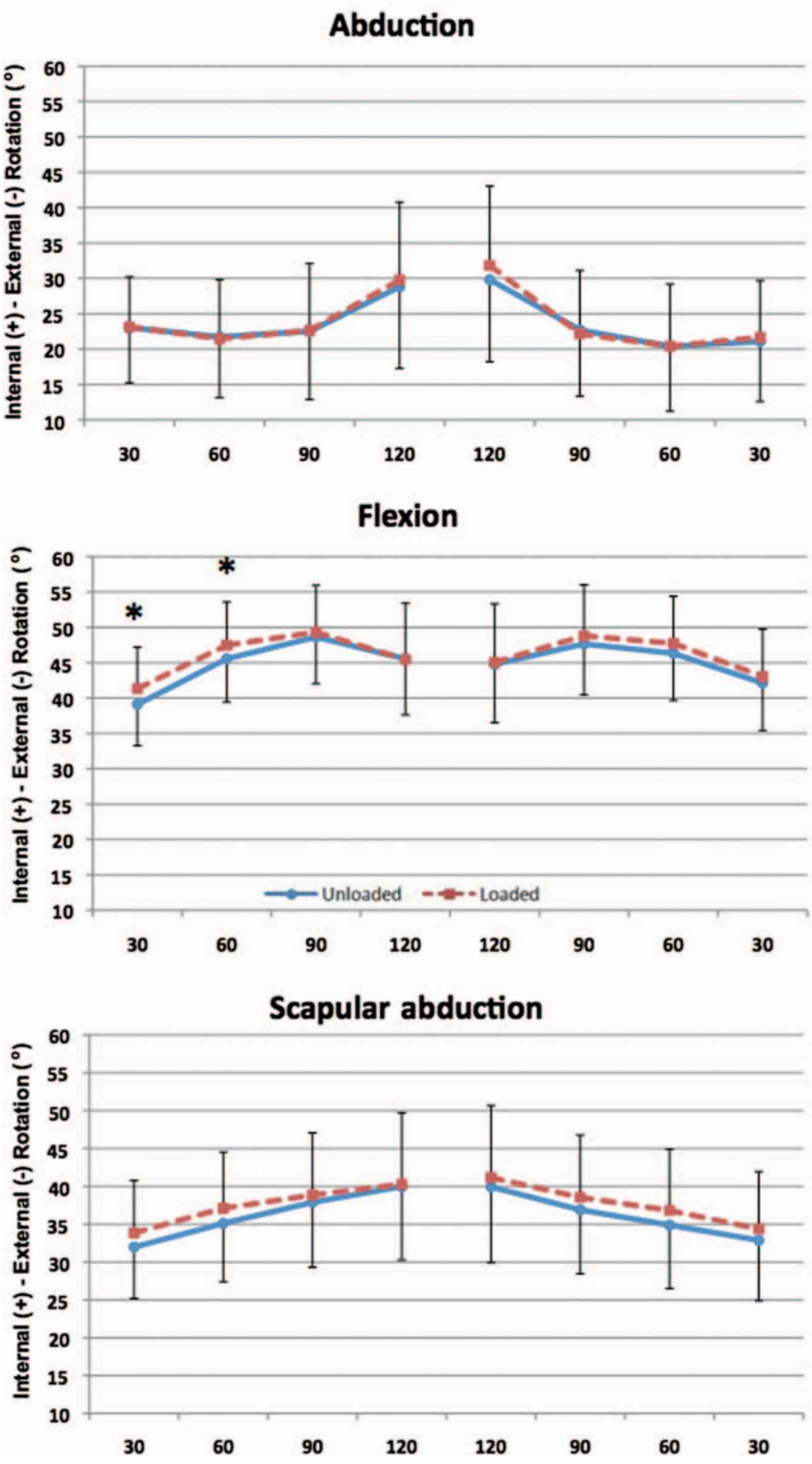


FIGURE 30.11 Scapular kinematics during resisted shoulder elevation exercise.

eventually affect the internal structures such as cartilage, tendons, ligaments, bones, and muscles. During single leg squat exercise on the knee joint, femur is pulled to flexion by gravity force (external load) and muscle exerts the force (internal load) including stretching of the other surrounded soft tissues to neutralize external load. If amount of the external force and its fulcrum is known, the internal forces could be calculated. In Additionally, the force contributions of ligaments and fasciae and other surrounding soft tissues can also be considered. Although researchers have described the load bearing capacity of the fasciae (Bogduk and Macintosh, 1984; Stecco et al., 2007), the research on the forces exerted by fasciae are still limited (McGill and Norman, 1988).

If we consider all kinetic chain segments together, the forces between body segments are produced by a combination of the reaction forces at each joint surface and the actions of the muscles crossing each joint.

Exercise training

In the era of evidence-based medicine, exercise therapy is the best available active treatment method for several neuro-musculo-skeletal disorders (Van den Ende et al., 1998; van der Lee et al., 2001; Taylor, Brown et al., 2004; Hayden et al., 2005; Valkenet Port et al., 2011). The effective and safe prescription of the exercise training begins with single exercise design. The Specific Adaptation to Imposed Demand (SAID) principle can be accepted as one of the most important basic concepts in the exercise therapy. SAID means that when the body is placed under some form of stress, it starts to make adaptations that will allow the body to get better at withstanding that specific form of stress in the future (Fox and Mathews, 1981). There could be various objectives of any exercise design including the parameters below but not limited to:

- to increase strength and endurance;
- to increase explosive power;
- to facilitate the muscles to sustain forces for a prolonged time;
- to increase or maintain muscular hypertrophy; and,
- to improve neuro-musculo-skeletal function.

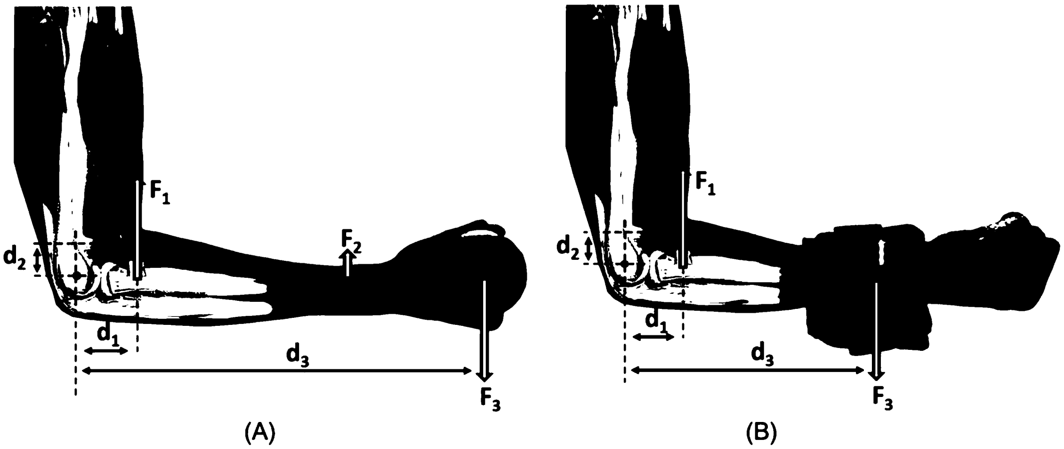
Based on a specific aim, the exercise training can be designed by using an appropriate approach and technique, considering the type of muscle contraction involved, the speed of movement and acceleration over different phases of movement, which are the exercise intensity, the rest intervals, the involved agonists and antagonists, and stabilizers and movers. Therefore, the exercise design is important for individuals with specific demands, and the biomechanical principles simply change stress in any particular exercise.

Open kinetic chain exercises

Open kinetic chain exercises do not require fixing of the terminal segment and allow the terminal segment to move freely (Gowitzke and Milner, 1988; Lephart and Henry, 1996; Camci et al., 2013). Open kinetic chain exercises usually aims for strengthening. Resistive exercises often used for strength training with using various equipment such as dumbbells, medicine balls, elastic bands, and weight machines. While applying external resistance to the relative limb, the clinicians should consider some principles that will change the loading.

As an example, consider the weighted biceps curl exercise. During this exercise, biceps brachii and brachioradialis muscles generate forces F_1 and F_2. Perpendicular distances between the lines of action of the forces and the center of rotation at the elbow joint are (d_1) and (d_2) respectively. F_3 represents the loading force and the d_3 represents the perpendicular distance between the lines of action of the forces and the center of rotation (Fig. 30.12).

The moment generated can be calculated as $M = F_1 \times d_1 + F_2 \times d_2 - F_3 \times d_3$. The greater distance between the action line of the force and the center of rotation of the joint (the greater the lever arm) result with the greater moment of the force (Fig. 30.12A). If the same amount of weight applied on the wrist with bag instead of holding



(A) (B)

FIGURE 30.12 Weighted biceps curl exercise, (A) using hand dumbbell, (B) weight bag at the wrist.

hand dumbbell, to flex the elbow joint, force generated by the muscles decreases as the d_3 decreases (Fig. 30.12B).

The range of motion on elbow joint during this exercise also affects the mechanical loading. If the biceps curl performs starting from 0° of elbow extension to elbow flexion, the length of the effort arm is continuously be increased. and mechanical advantage is going to be greatest at 85°–100° of elbow flexion. While the longer effort arm provides the mechanical advantage, as the muscle will be shorter and overlapped myofilaments in full range of elbow flexion reduces force capacity as it was first described by Gordon et al. (1966), defining the force-length relationship and its direct relation to the myofilament overlap. Therefore, if the full range of elbow flexion is chosen during the biceps curl exercise, the biceps muscle loses the force capacity.

The type of external load can alter the biomechanical demand of the exercise. Likewise, the elastic bands also provide some form of resistance, allow free range of motion, variable speed of movement, and progressive resistance. Based on their ease of use, low cost, and portability, elastic bands are frequently used in clinical practice to provide resistance in fitness and rehabilitation (Patterson et al., 2001). Elastic bands provide variable resistance based on physical properties such as the elongation of the elastic material (Hughes et al., 1999). However, earlier studies have shown that muscle activity and peak load during elastic-resistance exercise is similar to free-weight resistance exercise (Treiber et al., 1998; Hughes et al., 1999; Patterson et al., 2001; McMaster et al., 2009). On the other hand, recent studies have investigated electromyographic signals to compare muscle activation in resistance exercises using both elastic and conventional resistance showed that conventional resistance was found to be the favorable modality (Sundstrup et al., 2014; Vinstrup et al., 2017). In general, induced muscle activity while using conventional exercise equipments is greater than elastic resistance in the early concentric phase of the movement. However, when the elastic band is maximally elongated the induced muscle activities in both conditions are found similar. Biomechanically, unlike free weights, elastic bands do not provide resistance relying on gravity. Free weights only provide resistance in a vertical plane. With elastic bands, the resistance can also applied on horizontal plane as in shoulder PNF exercise which is accepted more functional, naturally by changing the direction of pull of the elastic bands (Page et al., 1993).

Closed kinetic chain exercises

There is variety of description of closed kinetic chain exercises. It is widely accepted that closed kinetic chain exercise requires weight-bearing position of the extremity by fixing the distal segment to a mobile or immobile object. Biomechanical studies support the rationale for advantages of applying closed kinetic chain exercises (Lutz et al., 1993; Yack et al., 1993; Wilk et al., 1996; Beynnon et al., 1997; Escamilla et al., 1998; Turgut et al., 2016). It is recommended especially for early knee rehabilitation (e.g. anterior cruciate ligament reconstruction) (Wright et al., 2008). Closed kinetic chain exercises often involve multi-joint movements and body weight bearing conditions which affect biomechanical and neuromuscular needs of the individuals (Tucker et al., 2010). There is agonist-antagonist muscular co-contraction around joints (Pincivero et al., 2000; Stensdotter et al., 2003), and articular compressive forces increase (Lutz et al., 1993) during closed kinetic chain exercise.

The squat exercise is commonly used exercise by physiotherapists and trainers, since there is scientific findings showing its effectiveness for improving muscle endurance, strength, and power (Fisher et al., 2011). The squat is a multi-joint exercise, designed to aim to improve muscular performance of the lower body. There is some modification of the squat exercises, such as the bodyweight squat, back-squat, front-squat, sumo-squat, split-squat, box-squat, or single-leg squat. However, commonly, the posture and mobility towards hip and knee flexion and ankle dorsiflexion are the important components. In this exercise, as a starting position, an individual is asked to keep standing position with feet shoulder-width apart, toes pointing straight ahead, and knees aligned over second and third toes. As much as 5–8° of external foot rotation is allowed in the starting position (Schoenfeld, 2010). Then, individual is asked to perform squat without any movement compensations such as increased knee valgus, lumbar lordosis, forward lean of the torso, and pronation of the foot. From biomechanical perspective, these compensations result in lower 1RM and unsafe loads.

Exercise training across lifespan

To promote and maintain health, American College of Sports Medicine (ACSM) provides an evidence-based recommendation for physical activity and exercise training for individuals across lifespan.

According to ACSM guidelines, adults need moderate aerobic activity for a minimum of 150 minutes weekly or vigorous aerobic activity for a minimum of 60 minutes weekly. As an example; individuals can perform moderate aerobics 30 minutes daily, 5 days weekly; or, individuals can perform vigorously intense cardio 20 minutes daily, 3 days weekly. Additionally, individuals should perform 8–10 different strengthening exercises, for 8–12 repetitions of each exercise twice weekly.

On the other hand, it is essential to promote youth population to participate more in physical activity. Of course, that prescribed physical activity should be appropriate for their age and enjoyable. Children and adolescents (ages between 6 through 17 years) should perform minimum of 60 minutes moderate to vigorous activity daily at least 3 days a week. The daily physical activity for children and adolescents should include muscle-strengthening and bone-strengthening exercises on at least 3 days a week.

However, same exercise program does not suitable for everyone, but it may help to see a sample exercise schedule that allow a person to start. This may include all the exercise program a person needs, from beginners to more advanced level of exercise.

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Index

Note: Page numbers followed by "*f*" and "*t*" refer to figures and tables, respectively.

A

Abduction (protraction), 165, 171
Abductor digiti minimi, 433
Abductor hallucis muscle, 432
Abductor pollicis brevis (APB), 248
Abductor pollicis longus (APL), 244, 249
Abductors, 386*t*
Accessory ligaments, 343*t*
Acetabular changes, 385, 386*t*
Acetabular dysplasia, 347, 383, 385
Acetabular fractures, 347
Acetabular index (AI), 387
Acetabulum, 341, 387, 493
Achilles tendinopathy, 130–131
Achilles tendon, 126, 413–414, 426, 428–429
  rupture, 126–127
Acromioclavicular joint, 162–163, 163*f*, 164*f*
Active assistive range of motion (AAROM), 255
Active range of motion (AROM), 255
Activity Energy Expenditure (AEE), 40
Acute ischemia, 367–368
Acute ruptures, 124
Adduction (retraction), 165, 171, 244
Adductor hallucis, 433
Adductor longus muscle, 518
Adductor pollicis, 249
Adductors, 386*t*
Adhesive capsulitis, 168–170
AEE. *See* Activity Energy Expenditure (AEE)
Aerobic metabolism, 368
Afferent-efferent feedback systems, 384
Aggregate field theory, 29–30
Aging, tendon and ligament, 138–139
Airway resistance, 359
Ala ossis ilii, 340
Alpha motor neurons, 444
Alveolus, 370–371
Ambulation profile, 505–506
American Academy of Kinesiology and Physical Education (AAKPE), 8–9
American College of Sports Medicine (ACSM), 536
Aminergic neurons, 444
Amphiarthrosis, 47
Anaerobic metabolism, 368
Anatomic dead space, 353
Angiogenesis, 85
Ankle and foot complex, 411
  bones of
    distal tibia, 411, 412*f*
    fibula, 411–412, 412*f*
    metatarsals, 415
    phalanges, 416
    tarsal bones, 412–415
  foot arches, 425–427
    medial longitudinal arch, 425, 425*f*
    MTP joints, 427*f*
    plantar fascia, 426, 426*f*
    transvers arch, 425–426
    windlass mechanism, 426–427, 427*f*
  joints of, 416–425
    ankle, 416–418
    distal intertarsal, 421, 424*f*
    distal tibiofibular, 416
    forefoot, 416
    intermetatarsal, 421, 424*f*
    interphalangeal, 425
    metatarsophalangeal, 422–424, 424*f*
    midfoot, 416
    midtarsal, 420–421, 421*f*, 422*f*
    proximal tibiofibular, 416
    rearfoot, 416
    subtalar, 419
    tarsometatarsal, 421, 424*f*
  muscles of, 427–435
    anterior, 427–428, 427*f*
    dorsal intrinsic, 434–435
    lateral group, 430–431
    plantar intrinsic, 431–434
    posterior, 428–430, 428*f*
Ankle joint, 54, 416–418
  articular capsule, 416
  lateral ligaments, 417–418, 418*f*
  medial collateral ligaments, 417, 417*f*
  mortise joint, 416
  movement at, 418–419, 419*f*
Ankle rocker motions, 505, 505*f*
Ankle sprain, 473
Annular ligament (AL), 193–194
Annulus fibrosus, 325
Anterior abdominal muscles, 333
Anterior and posterior longitudinal ligaments, 325–326
Anterior bundle of medial collateral ligament (AMCL), 193
Anterior cruciate ligament (ACL), 402, 404–405, 405*f*, 473
Anterior hip, 377*f*
Anterior interosseous nerve, neuropathy of, 258–259
Anterior longitudinal ligament, 315, 319
Anterior meniscofemoral ligament, 403–404
Anterior muscles, 427–428, 427*f*
  extensor digitorum longus, 428
  extensor hallucis longus, 427–428
  tibialis anterior, 427
Anterior sacroiliac ligament, 343*t*
Anterior superior iliac spines (ASIS), 345
Anterior talofibular ligaments, 417–418
Anteriorly shifted vertebra, 335–336
Anterolateral (AL) bundles, 405
Anteromedial (AM) bundles, 405
Anteversion angle, movements of hip joint, 380–381, 381*f*
Anti-gravity muscles, 478
Apoptosis, 84
Arm adductors, 184
  deltoid muscle, 184
  teres major muscle, 184
Arm elevators, 180–184
  biceps brachii, 182–183
  coracobrachialis muscle, 182
  deltoid muscle, 180–181, 181*f*
  infraspinatus muscle, 183
  subscapularis muscle, 183–184
  supraspinatus muscle, 181–182
  teres minor muscle, 183
Arm rotators, 184
Arms, bipedalism, 490
Arterioconstriction, 369–370
Artery morphogenesis, normal and narrowed, 367*f*
Arthrokinematics, 18, 19*f*, 290–293
  convex and concave rules, 52–53, 53*f*
  depression and elevation, 290–291
  lateral excursion, 291
  mastication, 291–293, 292*f*
  protrusion and retrusion, 291
  rolling, 52
  sliding, 52
  spinning, 52
  types, 52, 52*f*
Articular capsule, 192–193, 403, 416
Articular cartilage, 50
Articular disc, 286
  mechanical loading in, 294–295
Articular faces of thoracic vertebrae, 316*f*

Articulations, 192, 221–223
  carpal arch, 222–223
  intercarpal joints, 222
  midcarpal joint, 221–222
  radiocarpal joint, 221
Associative learning, 455
  classical conditioning, 455
  operant conditioning, 455
Ataxia, 451
Atherogenesis, 366, 369
Atherosclerosis, 370
Athetosis, 451
Athlete, elbow injuries in, 204–205
Atlanto-axial joint dislocation (AAD), 310–311
Attention deficit/hyperactivity disorder (ADHD), 451
Auditory system, 443–444
Autism Spectrum Disorders (ASD), 461
Autonomic nervous system, 31–32
Auxiliary group muscles, 316
Auxiliary muscles, 358
Axiohumeral muscles, 184–185
Axioscapular and axioclavicular muscles, 174–179
  scapulothoracic joint abductors, 178–179
  scapulothoracic joint adductors, 178
  serratus anterior muscle, 178–179, 179*f*
  trapezius muscle (upper portion), 174–178
    levator scapulae muscle, 176
    pectoralis minor muscle, 177–178, 185*f*
    rhomboid major and minor muscles, 176
    subclavius muscle, 178
    trapezius muscle (lower portion), 176–177
Axis of motion, 532

B

Balance and postural control
  balance maintaining strategies, 469–472
    clinical relevance, 470
    CoM and CoP behavior, 469–470
    CoP trajectory, 470–472
    posturography, 470
    stabilogram, 470
  center of gravity (CoG), 468
  center of mass (CoM), 468, 468*f*
  center of pressure (CoP), 468, 468*f*
  definition of, 467–469
  geocentric reference frame, 467–468
  integrative models, 468–469, 468*f*
  in pathological conditions, 472–473
    ankle sprain, 473
    anterior cruciate ligament rupture, 473
    chronic ankle instability, 473
    multiple sclerosis, 472
    nonspecific low back pain (NSLBP), 472–473
    Parkinson disease (PD), 472
    stroke, 472
  sensory-motor of, 469
Ball and socket joint, 49, 49*f*
Ballismus, 451
Basal ganglia, 446–447, 451
Bayesian processing, 480
Behavioral approach, motor learning, 454–455
  associative learning, 455
    classical conditioning, 455
    operant conditioning, 455
  learning and memory, classification, 454*f*
  nonassociative learning, 455
  perceptual learning, 455
Bending force, 23
Bennett fracture, 250, 251*f*
Bernoulli's law, 369
Bernstein's three-stage model, 459
Biceps brachii (BB) muscle, 182–183, 191, 197–198, 199*f*
Biceps femoris, 521
Biceps tendon injuries, 207
Bicondylar angle, 494, 494*f*
Bilateral facet joints, 326–328
Biomechanics
  A2 and A4 pulleys, 261
  of circulation. *See* Circulation, biomechanics of
  defined, 527
  embryo/fetus
    computational methods, 66–67
    mechanical features, 66
  of exercise design. *See* Exercise, biomechanics of
  uterus, mechanical features, 66
Bipedal gait, 496
Bipedal human walking, 489
Bipedalism, 489
  anatomical features indicative of, 491*t*
  bipedal gait, 496
  evolution of, 490–496, 492*f*
    arms and legs, 490
    feet and toes, 495–496, 495*f*
    hips, 493–494
    knee, 494–495
    pelvis, 492–493, 493*f*
    sacrum, 491–492
    skull, 490, 492*f*
    spine, 490–491, 492*f*
  food-carriage hypothesis, 489–490
  foramen magnum, 492*f*
  human pelvis with early ancestors, 493*f*
  infant-carriage hypothesis, 489–490
  locomotor efficiency hypothesis, 489–490
  postural feeding hypothesis, 490
  seed eating hypothesis, 490
  small-object feeding hypothesis, 490
  social display hypothesis, 489
  thermal radiation avoidance hypothesis, 489–490
  tool-use hypothesis, 489
Blood rheology, 370
Body segment movements, 3–4, 6*f*
Bolus flow, 370
Bone mineral density (BMD), 478
Bone tissue
  angiogenesis, 85
  apoptosis, 84
  architecture
    immature (woven) bone, 73, 73*f*, 74*f*
    mature bone (compact and spongy), 72–73, 72*f*, 73*f*
  auto/allograft application, 85–86
  bisphosphonates, 85–86
  bone formation, 85
  bone lining cells, 75, 75*f*
  degradation, 84
  diaphysis, 71
  epiphysis, 71
  extracellular matrix (ECM)
    components, 76
    inorganic, 76
    organic, 76–77
  life stages
    endochondral ossification, 82–83, 83*f*
    intra-embryonic mesoderm, 82
    membranous ossification, 82
    remodeling, 83–84, 83*f*
  mechanical properties
    bending, 82, 82*f*
    biomechanical behavior, 77–78, 79*t*
    compression, 79–80, 79*f*
    intrinsic properties, 78
    natural material, 77–78, 78*f*
    shear, 80–81, 81*f*
    tension, 80, 80*f*
    torsion, 81–82, 81*f*
  microstructure, 71
    cortical bone, 71
    mature/secondary bone, 72
    trabecular bone, 71
  mineral components, 74
  modalities, 84
  organic components, 74
  osteoarthritis (OA), 86, 87*f*
  osteoblasts, 74–75, 74*f*
  osteoclastogenesis, 84–85
  osteoclasts, 75–76
  osteocytes, 75, 84
  osteogenesis imperfecta (OI), 86–87
  osteolysis and mineralization, 85
  osteomyelitis, 86
  osteoporosis (OP), 86
  osteoprogenitor cells, 74
  regenerative and adaptive behavior, 84
Bones
  ankle and foot complex
    distal tibia, 411, 412*f*
    fibula, 411–412, 412*f*
    metatarsals, 415
    phalanges, 416
    tarsal bones, 412–415
  shoulder complex, 157–160
    clavicle, 157, 162*f*, 173*f*
    proximal-mid humerus, 159–160, 159*f*
    scapula, 157–159, 158*f*
    sternum, 160
Boutonniere deformity, 270
Brachioradialis (BR) muscle, 191, 198, 200*f*
Brain-derived neurotrophic factor (BDNF), 135–136
Broadman 22, 445
Broadmann 17, 445

C

Cadence (tempo), 501

Calcaneocuboid joint, 415, 420–421
  plantar ligaments of, 415
Calcaneofibular ligaments, 419
Calcaneus, 413–414, 414*f*, 425, 495
Capillary microcirculation, 369
Capitate, 219–220
Capitellum, osteochondritis dissecans of, 206
Capsules, 286–287
Capsuloligamentous complex, 169
Cardiac murmurs, 366
Carpal arch, 222–223
Carpal arthrodesis, carpal kinematics following, 236
Carpal bones, 213–220
  capitate, 219–220
  hamate, 220
  lunate, 216, 217*f*
    Kienböck's disease, 218–219
    lunate dislocation, 217–218
    morphology, 217
    pathologies, 217–219
  pisiform, 219
  scaphoid, 215–216
    fractures, 216
  trapezium, 219
  trapezoid, 219
  triquetrum, 219
Carpal kinematics, 228–231
  carpal arthrodesis, 236
  carpal tunnel pressure, 231
  effect of scaphoid excision on, 227
  dart-throwing motion (DTM), 229–230
  distal radius fracture, 235
  flexion and extension, 230–231
  functional wrist range of motion, 228–229
  global wrist motion, 228
    radiocarpal and midcarpal motion, 228
  perilunate dislocations, 231
  scapholunate instability, 235–236
  wrist arthrodesis position, 229
Carpal motions, wrist movements, 231–232
  column and row wrists, 232
  radial and ulnar deviation, 232
Carpal tunnel pressure, 231
Carpometacarpal (CMC) joints, 236–237, 240–247, 241*f*, 242*f*, 415
  abduction and adduction kinematics of, 244
  carpometacarpal osteoarthritis
    progression of, 246–247
    strength of the ligaments in, 246
  distribution of forces on thumb joints, 242–243
  flexion–extension kinematics of, 244
  Gamekeeper's thumb, 245–246
  innervation patterns of the ligaments, 247
  ligaments of, 244–245
  measurement of the thumb opposition, 244
  opposition kinematics of, 244
  osteoarthritis of thumb, 243
  second–fifth carpometacarpal joint motion, 241
  of second–fifth digits, 240
  stabile and mobile columns in grip activities, 240–241
  Stener lesion, 246, 247*f*
  of thumb, 241–242
Carpometacarpal osteoarthritis
  progression of, 246–247
  strength of the ligaments in, 246
Cartilage oligomeric matrix protein (COMP), 94
Cartilage tissue
  chondrocytes, 93
  collagens, 94
  elastic cartilage, 91
  extracellular matrix, 93–94
  fibrocartilage, 91
  glycoproteins, 94
  hyaline cartilage, 91, 92*f*
  interterritorial matrix, 93
  layers
    calcified cartilage zone, 92–93
    middle zone, 92
    superficial zone, 91–92
    transitional zone, 92
  life stages, 96–97
  mechanical properties
    collagen-proteoglycan matrix, 94–95
    compressive stress, 95
    elastic modulus, 95
    flow dependent mechanism, 94–95
    high-energy activities, 94
    immobility/lower activity rates, 96
    shear stress, 95
    solid phase, 95–96
    tensile stress, 95
    viscoelasticity, 94–95
    young modulus, 94–95
  microstructure, 91–94, 92*f*
  pathological conditions, 95*f*, 97–98, 98*f*
  pericellular matrix, 93
  proteoglycans, 93–94
  territorial matrix, 93
  thrombospondin, 94
  tissue fluid, 93
Cartilages, development of, 62
Cartilaginous joint, 48
Catecholamines, 371
Cell-cell communication, 122–123
Center of gravity (CoG), 23–24, 468, 516, 532
Center of mass (CoM), 36–37, 467–470, 468*f*, 480–481
Center of pressure (CoP), 468–473, 468*f*
  human gait, 502
  maximum and minimum amplitudes, 471
  mean CoP amplitude, 471
  sway area, 471
  sway path, 471
  sway velocity, 471
  total excursion (mm), 471
  trajectory, 470–472
Central nervous system
  basal ganglia, 30–31, 31*t*
  cerebellum, 31
  motor cortex, 30, 31*t*
Cerebellar ataxia, 451
Cerebellar fibers, 446
Cerebellum, 446, 457–458
Cerebral cortex, 445
Cerebral palsy (CP), 386–387, 451, 462, 505
  femur, 386–387
  spastic hip dysplasia *vs.* developmental hip dysplasia, 386, 387*t*
Cerebrovascular disease, 451
Cervical ligaments, 419
Cervical vertebral column, 303
  functional anatomy, 303–305
  instantaneous axis of rotation, 309–310
  kinematics of, 305–308
  kinetics of, 308–309
  in pathological conditions, 310–314
Childhood Apraxia of Speech, 461
Chorea, 451
Chronic ankle instability (CAI), 473
Chronic degenerative tendinopathies, 124
Chronic low back pain, 335
Chronic neck and back pain, 322
Chronic obstructive pulmonary disease (COPD), 320
Chronic respiratory diseases, 360
Chronic tendinopathy, 126
Chronophotograph, 3, 5*f*
Circulation, biomechanics of, 365
  blood flow, 365, 367
    in arteries and veins, 368–370, 369*f*, 370*f*
    in lungs, 370–371
  heart as pumping device, 365–368, 367*f*, 368*f*
    artery morphogenesis, normal and narrowed, 367*f*
    diastolic filling phase, 367
    fluid dynamics of valve, 366, 367*f*
    in isovolumetric state, 366–367
Classical conditioning, associative learning, 455
Clavicle, 157, 162*f*, 173*f*
Clinical gait analysis, 4
Closed and open chain motions, 18, 19*f*
Closed kinetic chain exercises, 536
Closed loop motor control, 3, 4*f*, 448
Closed skills, 459
Coccyx, 331
Cognitive approaches, 455–457
  memory, 456–457
  observational learning, 455–456
Cognitive loop, 445–446
Collateral ligament injury, 254
Collateral ligaments, 404, 419
  of interphalangeal joints, 424*f*
  lateral collateral ligament, 404
  medial collateral ligament, 404
  of metatarsophalangeal joints, 424*f*
Column and row wrists, 232
CoM. *See* Center of mass (CoM)
Compressive forces, 22–23
Concentric muscle contraction, 500
Conducting airways and alveoli, 353–354, 355*f*
Condyloid joint, 49, 49*f*
Congenital Atlanto-axial joint dislocation (CAAD), 310–311
Congruence angle, 397, 398*f*
Connective tissue disorders, 142

Constraint induced movement therapy (CIMT), 462
Controlled loading, 123
Coracobrachialis muscle, 182
Coracohumeral ligament, 168–169
Corollary discharge, 447
Corpus ossis ilii, 340
Corpus ossis ischii, 340
Corticosteroid injections, 130
Costo-corporeal joints, 321
Costotransverse joints, 319, 356
Costovertebral joints, 315, 356
Creep phenomenon, 134
Crimp pattern, tendon and ligament, 116
Cruciate ligaments, 404–405, 405*f*
  anterior cruciate ligament (ACL), 405, 405*f*
  gait mechanics in ACL-deficient knee, 405
  posterior cruciate ligament (PCL), 405, 405*f*
Cuboid, tarsal bones, 415
Cuneiforms, tarsal bones, 414–415, 415*f*
Cyclic hydrostatic pressures, 123–124
Cytoskeletal contracture, 125*t*
Cytoskeletal proteins, 477–478

D

Dart-throwing motion (DTM), 211, 229–230
Decreased lumbar lordosis, 331–332
Deep fascia, 149–150, 152
Degenerative arthritis, 97, 384
Degenerative processes, 321
Degenerative spinal disease, 334
Degenerative tendinopathy, 124, 126
Degree of freedom (DOF), 51, 51*f*, 529–531
Deltoid ligaments, 419
Deltoid muscle, 180–181, 181*f*, 184
Depression and elevation, 290–291
Deteriorated scapular kinematics, 174–175
Developmental coordination disorders (DCD), 451, 461
Developmental dysplasia of the hip (DDH), 384–385, 387*t*
  acetabular changes, 385, 386*t*
  capsule, changes in, 385
  femoral head changes, 385
  femoral-pelvic muscles, 385
  ligamentum teres, 385
  limbus, 385
  pulvinar, 385
  vs. spastic hip dysplasia, 386, 387*t*
Diaphragm, 320, 356–358, 357*f*
Diarthrosis, 47
Diabetes mellitus, 141
Diabetic foot, 152–153, 153*f*
Diastolic filling phase, 367
Diet-Induced Thermogenesis (DIT), 40
Digital flexor pulleys, 261
Digital flexor sheath and pulley system, 260–262
  biomechanical effect of the A2 and A4 pulleys, 261
  digital flexor pulleys, 261
  mechanical analysis of palmar aponeurosis, 261
  palmar aponeurosis pulley, 261
  thumb flexor tendon sheath, 262
Direct calorimetry measurement method, 41
Disc displacement with reduction (DDwR), 296–297, 297*f*
Disc displacement without reduction (DDwoR), 297–298, 298*f*
Disc herniation, 334
Distal femur, articular surface of, 394*f*
Distal intertarsal joints, 421, 424*f*
Distal mobilizers, 179–185
  scapulohumeral muscles, 179–185
  arm adductors, 184
  arm elevators, 180–184
  arm rotators, 184
  axiohumeral muscles, 184–185
  latissimus dorsi muscle, 184–185
  pectoralis major muscle, 184
Distal radioulnar joint (DRUJ), 211
Distal radius, 211–212
Distal radius fracture, carpal kinematics following, 235
Distal tibia, 411, 412*f*
Distal tibiofibular joint, 416
Distal ulna, 212–213
  ulnar variance on wrist biomechanics, 213
Distonnia, 451
Distribution of forces on the joints of the thumb, 242–243
DIT. *See* Diet-Induced Thermogenesis (DIT)
DLW method. *See* Doubly labeled water (DLW) method
Dlx gene, 64
Dorsal column-medial lemniscal (DCML) pathway, 444
Dorsal interosseal muscles, 273, 434, 434*f*
Dorsal intrinsic muscles, 434–435
Dorsal radiocarpal ligaments (DRCs), 224
Dorsal-spinocerebellar pathways, 446
Dorsiflexor muscles, 427
Dorsi-plantar flexion of ankle, 419
Doubly labeled water (DLW) method, 40–41
Down syndrome, 461
Downward rotation, 166
Dupuytren's disease, 141
Dynamic compliance, 359
Dynamic Q angle, 401
Dyskinesia, 451

E

Eccentric exercise, 130–131
Eccentric muscle contraction, 500
Ecological theory of motor learning, 453
Edinburgh Visual Gait Analysis system, 506
Effort force, 531
Egyptian foot, 415
Ekstensors, 386*t*
Eksternal rotators, 386*t*
Elastic cartilage, 91
Elastic fibrinogenesis, 115
Elasticity, 150
Elastin, 117, 132
Elbow complex, kinesiology of, 191
  anatomy, 191
  anterior elbow pain, 207
    biceps tendon injuries, 207
    median nerve compression, 207
  arthrology, 192–195
    articular capsule, 192–193
    articulations, 192
    forearm and interosseous membrane, 194–195
    lateral collateral ligament (LCL), 193–194
    medial collateral ligament (MCL), 193
  elbow injuries in the athlete, 204–205
  elbow kinesiology in acute traumatic injuries, 203–204
    elbow fracture dislocations, 203–204
    elbow simple dislocations, 203
  elbow trauma and its sequela, 204
    stiffness, 204
  instability, 202–203
  kinematics, 195–197
    flexion and extension, 196
    pronation and supination, 196–197
  lateral elbow pain, 206
    lateral epicondylitis and radial tunnel syndrome, 206
    osteochondritis dissecans (OCD) of capitellum, 206
  medial elbow pain, 205–206
    flexor-pronator muscle injuries and medial epicondylitis, 205
    medial collateral ligament injury, 206
    ulnar neuropathy, 205
  muscles, 197–199
    biceps brachii, 197–198, 199*f*
    brachioradialis, 198, 200*f*
    pronator teres, 198
    supinator muscle, 198–199
    triceps brachii, 198, 201*f*
  osteology, 191–192
    humerus, 191–192
    radius, 192
  posterior elbow pain, 207
    olecranon bursitis, 207
    olecranon stress fracture, 207
    posterior olecranon impingement, 207
    triceps tendon rupture, 207
  stability, 199–202
  surface anatomy, 191
Elbow joint, 55
Electrogoniometric methods, 383–384
Electromagnetic tracking systems, 326–328
Electromyography (EMG), 335, 508, 509*f*, 510*f*
Embryologic development
  blastocyst, 61
  cartilages, 62
  cranio-caudal mechanism, 61
  dermomyotome, 61–62
  embryoblasts, 61
  endochondral bone formation, 62–63
  epiblast, 61
  hipoblast, 61

  - human extremity development, 63
  - intramembranous ossification, 62
  - mesenchymal cells, 61–62
  - molecular mechanisms of muscloskeletal development
    - Dlx gene, 64
    - fibroblast growth factor (FGF), 65
    - hedgehog family, 65
    - Helix Loop Helix Proteins, 65
    - homeodomain proteins, 64
    - Hox gene, 64
    - Lim proteins, 64
    - Msx gene, 64
    - Pax gene, 64
    - POU gene, 64
    - receptor molecules, 66
    - signaling molecules, 65
    - T-box (Tbx) gene, 65
    - transforming growth factor (TGF)-β, 65
    - Wnt family, 65
    - zinc finger transcription factors, 65
  - muscloskeletal system, 61–63
  - myoblasts, 62
  - myotomes, 62
  - notochord, 61–63
  - paraxial mesoderm, 61–62
  - somites, 61–62
  - syndetome, 61–62
- Energetics
  - Activity Energy Expenditure (AEE), 40
  - bipedal *vs.* quadrupedal locomotion, 37–39
  - direct calorimetry, 41
  - doubly labeled water (DLW) method, 40–41
  - indirect calorimetry. *See* Indirect calorimetry measurement method
  - mechanical energy sources, 36
    - walking and running, 39
  - metabolic energy sources, 36
    - walking and running, 39
  - movement patterns, 35–36
  - Resting Energy Expenditure (REE), 40
  - terrestrial locomotion, 36–37
  - Thermic Effect of Food (TEF), 40
  - Total Energy Expenditure (TEE), 40
- Energy, 36
- Enthesis, 116–117
- Enthesopathy, 125*t*
- Episodic memory, 456
- Epitenon, 116
- Erector spinae muscles, 332
- Estrogen, 139
- Excessive flexion injuries, 321
- Excessive lateral transition, 397–398
- Exercise-based rehabilitation, 131
- Exercise, biomechanics of, 527–531
  - concepts of, 531–533
    - base of support area in exercise set-ups, 533*f*
    - center of gravity (CoG), 532
    - effort force, 531
    - force on axis (fulcrum), 531
    - kinematic analysis, 508*f*, 533
    - kinetics, 533
    - lever system, 531, 531*f*
    - movement, 532–533
    - resistive force, 531
    - scapular kinematics, 534*f*
    - torque, 532
    - types of motion, 532–533
    - wall press exercise, 532*f*
  - degree of freedom in exercise, 529–531
  - force, 528
  - internal biomechanics, 533–535
  - movement planes, 528–529, 529*f*
  - principle of, exercise
    - individuality, 527
    - overload, 527
    - progressive overload, 527
    - rest, 527
    - reversibility, 527
    - specificity, 527
    - trainability, 527
    - variability, 527
  - training, 535–536
    - across lifespan, 536–537
    - closed kinetic chain exercises, 536
    - open kinetic chain exercises, 535–536, 535*f*
  - velocity, 528
  - work, 528
- Exoskeleton, 118
- Expiratory muscles, 358
- Explicit learning, 454
- Extension strength *vs.* flexion strength, knee joint, 403
- Extensor carpi radialis brevis (ECRB), 199
- Extensor carpi radialis longus (ECRL), 199, 233–234
- Extensor carpi ulnaris muscle, 234
- Extensor digitorum brevis, 434–435
- Extensor digitorum communis (EDC), 211, 264–265
- Extensor digitorum longus, 428
- Extensor hallucis brevis, 434–435
- Extensor hallucis longus, 427–428
- Extensor indicis proprius (EIP) tendons, 211
- Extensor muscles, 478
- Extensor pollicis brevis, 249–250
- Extensor pollicis longus (EPL) tendon, 211, 250
- Extensor system, 263–271
  - Boutonniere deformity, 270
  - extensor mechanism, 266
  - extensor digitorum communis, 264–265
  - extensor zones, 263–264
  - juncture tendinum in extensor tendon injuries, 266
  - muscles, 264–265
  - relative motion concept, 270–271
  - retinacular ligaments, 267–268
  - sagittal band injury, 266–267
  - swan neck deformity, 268–270
- External fixation, 346–347
- External forces, 22
- External intercostal muscles, 358
- External oblique abdominal muscles, 333
- Extracellular matrix (ECM), 93–94, 115, 117, 122, 132
  - components, 76
  - inorganic, 76
  - organic, 76–77
- Extra-thoracic component, 353
- Extrinsic carpal ligaments, 224
- Extrinsic extensor muscles, 233
- Extrinsic, restrictive lung disorders, 361–362

F

- Facet joints, 315, 328–331, 330*f*, 331*f*
  - alignment, 321
  - hypertrophy, 334
  - joint capsule and articular process orientation of, 331*f*
  - positions during standing and sitting, 330*f*
- Facultative bipedalism, 490
- Fahraeus Lindqvist effect, 370
- Fascia, 149–152
  - biomechanics of, 150
  - deep, 149–150
  - defined, 149, 151–152
  - emotion, effects on, 150–151
  - fascial chain/fascial trains, 150
  - function of, 150
  - pathologies
    - diabetic foot, 152–153, 153*f*
    - frozen shoulder, 152
    - hypermobility, 152
    - plantar fasciitis, 152
    - trigger points, 153
  - proprioception, 151–152, 151*f*
  - subserous, 149–150
  - superficial, 149–150
  - surgery, effect on, 151
- Federation of International Robot-Sport Association (FIRA), 9
- Feet, bipedalism, 495–496, 495*f*
- Femoral head changes, developmental dysplasia of the hip, 385
- Femoral movements on pelvis, 381–382, 381*f*, 382*f*
- Femoral varus derotation osteotomy, 387–388
- Femoral-pelvic muscles, developmental dysplasia of the hip, 385
- Femoroacetabular impingement (FAI) syndrome, 389
- Femur, 386–387
- Femurs angle, 494
- Fibrillar organic matrix, 76
- Fibroblast cells, 132
- Fibroblast growth factor (FGF), 65
- Fibrocartilage, 91
- Fibrocartilaginous enthesis, 116–117
- Fibronectin, 117
- Fibrosis, 152
- Fibrous enthesis, 116–117
- Fibrous joint, 47–48
- Fibula, 411–412, 412*f*
- FIRA. *See* Federation of International Robot-Sport Association (FIRA)
- First dorsal interosseous, 250
- Fitts and Posner three-stage model, 459
- Fitts' law, 458–459
- Flexion and extension, 170–171, 196, 230–231
- Flexion–extension kinematics of first carpometacarpal joint, 244

Flexion strength *vs.* extension strength, knee joint, 403
Flexor carpi radialis (FCR) muscle, 215–216, 235
Flexor carpi ulnaris (FCU) muscle, 219, 234–235
Flexor digiti minimi (FDM), 220, 433
Flexor digitorum brevis, 432–433
Flexor digitorum longus, 430
Flexor digitorum profundus (FDP), 256–258
Flexor digitorum superficialis (FDS) muscles, 256–258, 258*f*
Flexor hallucis brevis, 432
Flexor hallucis longus, 430
Flexor pollicis brevis (FPB), 219, 248
Flexor pollicis longus (FPL), 256, 258
Flexor pulley system of thumb, 263*f*
Flexor system, 256–257
Flexor tendon zones, 259–260, 259*f*
Flexor tendons, biomechanical properties of, 262–263
Flexor-pronator muscle injuries and medial epicondylitis, 205
Flexors, 386*t*
  knee flexors. *See* Knee flexors
  plantar flexors, 514, 520
Fluid shear stress (FSS), 81
Fluoroquinolones, 142
Food-carriage hypothesis, 489–490
Foot arches, 425–427
  medial longitudinal arch, 425, 425*f*
  MTP joints, 427*f*
  plantar fascia, 426, 426*f*
  transvers arch, 425–426
  windlass mechanism, 426–427, 427*f*
Foramen magnum, 492*f*
Force plate, 500
Forces, 36
  components, 20
  definition, 20
  externally applied resistances, 22–23, 22*f*
  of quadriceps femoris muscle, 20, 20*f*
  resultant force, 20, 21*f*
  types
    friction, 21–22, 22*f*
    gravity, 20–21
    muscles, 21, 21*f*
Forearm and interosseous membrane, 194–195
Forearm supination-pronation exercise, 529, 530*f*
Forefoot, 416
Forefoot Rocker, 505
Fourth industrial revolution, 9
Free body diagram, 24, 24*f*
Free-weight resistance exercise, 536
Frequency, intensity, time and type of exercise (FITT), 527
Friction, 21–22, 22*f*
Froment sign, 249–250, 249*f*
  abductor pollicis longus (APL), 249
  extensor pollicis brevis, 249–250
  extensor pollicis longus, 250
  first dorsal interosseous, 250
Frozen shoulder. *See* adhesive capsulitis
Functional mobility test (FMT), 480–481
Functional scoring method, 505–506
Functional units of foot, 415*f*
Functional wrist range of motion, 228–229

G

Gaenslen's test, 336
Gait, 450*f*
  ACL-deficient knee, mechanics in, 405
  analysis, 38–39
  patterns, 8
  pelvis motion in the sagittal plane, 345*f*
  speed, 501
Gait cycle, 3, 6–7, 500, 503
  stance phase, 503–504
  sub-phases, 511
  swing phase, 503–504
Gait deviation index (GDI), 7
Gait profile score (GPS), 7
Gamekeeper's thumb, 245–246
Gamma motor neurons, 444
Gastrocnemius, 402–403, 428–429, 478, 517–518
GDI. *See* Gait deviation index (GDI)
Geocentric reference frame, 467–468
Glenohumeral (capsular) ligaments, 169
Glenohumeral internal rotation deficit (GIRD), 174
Glenohumeral joint, 167–174, 167*f*, 169*f*, 170*f*, 171*f*
  adhesive capsulitis, 168–170
  kinematics, 170–174
    glenohumeral internal rotation deficit (GIRD), 174
    subacromial impingement syndrome and scapulohumeral rhythm, 171–173
Glenoid labrum, 167*f*
Global wrist motion, 228
  radiocarpal and the midcarpal motion, 228
Gluteal muscles, 326
Gluteus maximus muscle, 331–332, 334, 379–380
  adductors, 379–380
  deep layer, 379
  superficial layer, 379
Gluteus medius insufficiency, 388
Gluteus medius muscle, 379, 379*f*, 388
Gluteus minimus muscle, 379
Glycoproteins, 94
GPS. *See* Gait profile score (GPS)
Graviceptor, 477, 479
Gravi-sensitive proteins, 477–478
Greek foot, 415
Grip activities, role of stabile and mobile columns in, 240–241
Ground reaction forces (GRF), 490–491, 500, 509*f*, 514–516
Gymnast's wrist, 213

H

Habitual bipedalism, 490
Habituation, 455
Hagen-Poiseuille law, 369
Hallux valgus, 425
Halsband's model, motor learning, 459
  advanced stage, 459
  initial stage, 459
  intermediate stage, 459
Hamate, 220
Hamstrings biomechanics, 401–402, 401*t*
Hamstrings muscles, 334, 401, 401*t*, 402*f*
  origin and insertion, 401*t*
Hand, kinesiology of, 236–282
  antideformity position of, 255
  artrology, 240–275
    biomechanical properties of flexor tendons, 262–263
    carpometacarpal joints, 240–243
    digital flexor sheath and pulley system, 260–262
    extensor system, 263–271
    first carpometacarpal joint kinematics, 243–247
    flexor tendon zones, 259–260, 259*f*
    interphalangeal joints of the fingers, 253–259
    intrinsic muscles, 271–275
    kinematics, 252–253
    muscles, 248–252
  functional position of, 255
  osteology, 238–240
    metacarpals, 238–239
    phalanges, 238–240, 241*f*
Head-down tilt bed rest (HDBR), 482
Heart valve diseases, 365
Heat, 36
Heavy slow resistance exercise, 131
Hedgehog family, 65
Heel Rocker, 505
Heel strike phase, 511–512
Helix Loop Helix Proteins, 65
Hemiballismus, 451
Henneman size principle, 35
Heterozygous familial hypercholesterolemia, 141
HFI. *See* Hip flexor index (HFI)
Hinge joint, 48, 49*f*
Hip extensors, 522–524
Hip flexor muscles, 520
Hip, kinesiology of, 375
  acetabulum, 341, 341*f*, 375–376
  anterior capsule and ligaments, 376*f*
  femoral head and neck, 376
  hip joint biomechanics, 380
  ligaments of hip joint, 376–377
    iliofemoral ligament, 376
    ischiofemoral ligament, 377
    ligamentum teres (foveal ligament), 376, 376*f*
    pubofemoral ligament, 377
  movements of hip joint, 380
    anteversion angle, 380–381, 381*f*
    femoral movements on pelvis, 381–382, 381*f*, 382*f*
    hip joint, walking and running, 383–384
    inclination angle, 380

    - pelvis movements on femur, 382–383, 382*f*, 383*f*
    - proprioceptive and kinesthetic issues of hip region, 384
  - muscle dynamics, 377–380
    - anterior hip, 377*f*
    - gluteus maximus muscle, 379–380
    - gluteus medius muscle, 379, 379*f*
    - gluteus minimus muscle, 379
    - iliacus muscle, 379
    - obturator externus muscle, 378
    - obturator internus muscle, 378
    - piriformis muscle, 377–378
    - posterior hip, 378*f*
    - Psoas major muscle, 378
    - quadratus femoris muscle, 378
    - tensor fascia lata muscle, 379
  - muscles, primary/secondary actions, 386*t*
  - pathologies, 384–388
    - cerebral palsy, hip joint in, 386–387
    - developmental dysplasia of hip (DDH), 384–385
    - meningomyelocele, hip joint in, 387–388
    - neuromuscular hip, 384
    - pelvic obliqueness, 388
  - pathomechanics in orthopedic conditions, 388–390
    - femoroacetabular impingement (FAI) syndrome, 389
    - hip endoprostheses, 389–390
    - osteoarthritis, 388–389
    - proximal femur fractures, 389
  - pelvis, 375
- Hip flexor index (HFI), 7
- Hips, 54–55
  - abduction and adduction, 381–382
  - abductor muscles, 493
  - bipedalism, evolution of, 493–494
  - dislocation, 375, 387–388
  - dysfunction, 384
  - endoprostheses, 389–390
  - external rotation and internal rotation, 382
  - flexion and extension, 381
  - instability, 384
  - pelvis, 343
- Histamine, 371
- Homeodomain proteins, 64
- Homeostasis, 140
- Hooke's law, 367–368
- Hox gene, 64
- Human gait, 499
  - ambulation profiles, 505–506
  - defined, 499
  - development, 502–503, 502*f*, 503*f*, 504*f*
  - electromyography (EMG), 508
  - energy consumption, 508–509
  - initial contact, 511–512, 513*f*
  - initial swing phase, 520–521, 521*f*, 522*f*
  - kinematic analysis, 506–507, 508*f*
  - kinetic analysis, 507–508
  - loading response, 512–515, 513*f*, 514*f*, 515*f*
  - lower extremity movements, 512*t*
  - methods in gait analysis, 505
  - mid-stance phase, 515–516, 516*f*
  - mid-swing phase, 521, 522*f*, 523*f*
  - normal gait, 503–505, 504*f*, 505*f*
  - observational gait analysis (OGA), 506, 507*t*
  - physical evaluation and functional scales, 510–511
  - plantar pressure analysis, 509–510, 510*f*, 511*f*
  - pre-swing phase, 518–520, 519*f*, 520*f*
  - sub-phases, 511, 512*f*, 512*t*, 513*f*, 514*f*
  - terminal stance phase, 516–518, 518*f*, 519*f*
  - terminal swing phase, 521–524, 523*f*, 524*f*
  - terminology, 500–502
    - cadence (tempo), 501
    - center of pressure (CoP), 502
    - concentric muscle contraction, 500
    - eccentric muscle contraction, 500
    - gait speed, 501
    - ground reaction force (GRF), 500, 509*f*
    - isometric muscle contraction, 500
    - joint moment *(M)*,, 500
    - joint power, 501
    - kinematics, 500
    - kinetics, 500
    - moment of inertia, 500–501
    - stance phase, duration of, 502
    - step length, 501
    - stride duration, 502
    - stride length, 501
    - swing phase, duration of, 502
- Humanoid robots, 7
- Humerus, 159
- Hyaline cartilage, 91, 92*f*
- Hybrid/cemented endoprosthesis, 390
- Hypercholesterolemia, 141
- Hyperextension of hip, 381
- Hypermobility, 152
- Hypertrophy, 365
- Hyperuricemia, 141
- Hypoxia, 371

- Iliacus muscle, 379
- Iliocostalis lumborum muscle, 332
- Iliofemoral ligament, 376
- Iliopsoas muscle, 332–333
- Iliotibial tract (ITT), 406
- Ilium, 340
- Immature (woven) bone, 73, 73*f*, 74*f*
- Implicit learning, 454
- Impulsive mechanical stimulation, 478
- Inclination angle, 380
- Indirect calorimetry measurement method
  - accelerometer, 41
  - advantages and limitations, 41, 42*t*
  - bioelectrical impedance analysis, 42
  - circulatory, 41
  - dietary questionnaires, 42
  - heart rate monitor, 41
  - heat and movement sensors, 42
  - pedometer, 41
  - physical activity records, 42
  - predictive equations, 42
  - respiratory, 41
  - self-report methods, 42
- Infant-carriage hypothesis, 489–490
- Inferior articular process, 330–331
- Inflammatory phase, tendon healing, 127–129, 129*t*
- Infrahyoidal muscles, 289
- Infraspinatus muscle, 183
- Initial swing phase, human gait, 520–521, 521*f*, 522*f*
- Innervation, 289
- Innervation patterns of ligaments, 247
- Inorganic extracellular matrix, 76
- Inspiratory muscles, 356–358
- Insulin-like growth factor (IGF-I), 123
- Integrin, 122–123
- Intercarpal joints, 222
- Intercostal muscles, 320
- Intermetatarsal joints, 421, 424*f*
- Internal fixation, 346
- Internal forces, 22
- Internal oblique muscles, 333
- Internal rotation, 166
- Internal rotators, 386*t*
- Interneurons of flexor muscles, 446
- Interoception, 151
- Interosseous ligaments, 419
- Interosseous membrane (IOM), 194–195
- Interosseus sacroiliac ligament, 343*t*
- Interphalangeal (IP) joint, 220, 425
  - collateral ligaments of, 424*f*
  - of fingers, 253–259
    - anterior interosseous nerve, neuropathy of, 258–259
    - antideformity position of the hand, 255
    - collateral ligament injury, 254
    - documentation of range of motion measurements, 256
    - flexor digitorum profundus, muscle test of, 257–258
    - flexor digitorum superficialis, 257–258
    - flexor pollicis longus, 258
    - flexor system, 256–257
    - functional position of the hand, 255
    - Linburg–Comstock anomaly, 258
    - motion values, normative range of, 256
    - quadriga phenomenon, 257
    - range of motion assessments, 255–256
    - volar plate injury, 254
- Interspinous ligament, 315
- Intertransversarii lumborum muscles, 332
- Interval scoring methods, 505
- Intervertebral discs, 326–328
- Intraligamentous vasculature, 133
- Intra-thoracic components, 353
- Intrinsic carpal ligaments, 227–228
- Intrinsic minus, 273–274
- Intrinsic muscles, 271–275
  - dorsal interosseal muscles, 273
  - intrinsic minus, 273–274
  - intrinsic muscle test, 273
  - intrinsic plus position, 274–275
  - lumbrical muscles, 272–273
  - palmar interosseal muscles, 273
- Intrinsic plus position, 274–275
- Intrinsic, restrictive lung disorders, 361–362

- Ischiofemoral ligament, 377
- Ischium, 340
- Isometric muscle contraction, 500
- Isthmus with hourglass deformity, 385

J

- Joint moment *(M)*,, 500
- Joint power, 501
- Joint receptors, 34
- Joints
  - arthrokinematics
    - convex and concave rules, 52–53, 53*f*
    - rolling, 52
    - sliding, 52
    - spinning, 52
    - types, 52, 52*f*
  - classification, 47–52, 48*t*
  - closed kinematic chain, 53
  - complexity, 47
  - congruency, 53–54, 54*t*
  - congruous–incongruous relationships
    - ankle joint, 54
    - contact area of, 54–55, 55*f*
    - elbow joint, 55
    - hip joint, 54–55
    - intervertebral articular facets, 55
    - knee joint, 54–55
    - midcarpal joint, 55
    - shoulder joint, 55
    - subtalar joint, 54
    - tibiofemoral joint, 54–55
    - wrist joint, 55
  - diseases of
    - osteoarthritis (OA), 56
    - rheumatoid arthritis (RA), 56
  - functional classification, 47
  - open kinematic chain, 53
  - osteokinematics, 52
  - patho-architecture, 55–56
  - shoulder complex, 160–174
    - acromioclavicular joint, 162–163, 163*f*, 164*f*
    - glenohumeral joint, 167–174, 167*f*, 169*f*, 170*f*, 171*f*
    - scapulothoracic joint, 163–166, 165*f*, 166*f*
    - sternoclavicular joint, 160–162, 161*f*
  - structural classification
    - ball and socket joint, 49, 49*f*
    - cartilaginous joint, 48
    - condyloid joint, 49, 49*f*
    - fibrous joint, 47–48
    - hinge joint, 48, 49*f*
    - pivot joint, 48–49, 49*f*
    - plane joint, 50, 50*f*
    - saddle joint, 49, 49*f*
    - synovial joint, 48, 50. *See also* Synovial joint
    - tissue type, 47
- Juncture tendinum in extensor tendon injuries, 266

K

- Kapandji index, 245*f*
- Kienböck's disease, 213, 218–219
- Kinematics
  - arthrokinematics, 18, 19*f*
  - closed and open chain motions, 18, 19*f*
  - exercise, biomechanics of, 533
  - human gait, 500, 506–507
  - joint levels, 18, 19*f*
  - lower extremity movements, 18
  - of lumbar vertebral column, 326–331
  - osteokinematics, 18
  - rotational movements, 17
  - translation movements, 17
  - upper extremity movements, 18
- Kinesiological electromyography, 5–6
- Kinetic energy, 367
- Kinetics, 533
  - center of gravity (COG), 23–24
  - exercise, biomechanics of, 533
  - forces. *See* Forces
  - free body diagram, 24, 24*f*
  - human gait, 500, 507–508
  - of lumbar vertebral column, 331–334
  - movement analysis, 18
  - torque, 23
  - variables, 20
- Knee, bipedalism, 494–495
- Knee extensors, 514
  - quadriceps femoris, 399, 400*f*
    - function of, 400–401
  - quadriceps (Q) angle, 401
    - defined, 401
    - dynamic Q angle, 401
    - supine *vs.* standing, 401
    - women *vs.* male, 401
  - rectus femoris, 399, 400*f*
  - vastus medialis *vs.* vastus lateralis, 399–400, 400*f*
- Knee flexors
  - gastrocnemius, 402–403
  - hamstrings biomechanics, 401–402, 401*t*
  - hamstrings muscles, 401, 401*t*, 402*f*
    - origin and insertion, 401*t*
  - pes anserinus, 402, 403*f*
  - popliteus, 402
- Knee joint, 54–55, 393
  - capsule, 403
  - muscular actions, 399–403
    - extension strength *vs.* flexion strength, 403
    - knee extensors, 399–401
    - knee flexors. *See* Knee flexors
  - patellofemoral joint, 396–399
    - normal alignment *vs.* malalignment, 397–398
    - patella, 396, 397*f*
    - patellofemoral contact area, 398, 399*f*
    - patellofemoral joint stress, 399
    - patellofemoral motion, flexion and extension, 398
    - patellofemoral reaction force (PFRF), 399, 399*f*
    - trochlear groove, 396–397, 397*f*
  - tibiofemoral joint, 393–396, 394*f*, 394*t*
    - distal femur, articular surface of, 394*f*
    - lateral condyles *vs.* medial condyles, 394*t*
    - motions, 394–395
    - normal alignment *vs.* malalignment, 393–394
    - proximal tibia, articular surface of, 394*f*
    - screw-home (locking) mechanism, 395–396, 396*f*
  - tibiofemoral joint passive static restraints, 403–406
    - collateral ligaments, 404
    - cruciate ligaments, 404–405, 405*f*
    - knee joint capsule, 403
    - meniscus, 403–404, 404*f*
    - patellofemoral joint restraints, 406
    - posterolateral corner (PLC) restraints, 406

L

- Laplace's law, 354
- Lateral collateral ligament (LCL), 193–194, 404, 417–418, 418*f*
- Lateral compression test, 348
- Lateral condyles *vs.* medial condyles, 394*t*
- Lateral epicondylitis and radial tunnel syndrome, 206
- Lateral excursion, 290–291
- Lateral extrinsic muscle group, 430–431, 431*f*
  - peroneus brevis, 431
  - peroneus longus muscle, 430–431
- Lateral group muscles, 430–431
- Lateral ligaments, ankle joint, 417–418, 418*f*
- Lateral longitudinal arch (LLA), 425*f*
- Lateral pterygoid muscle, 288–289
- Lateral ulnar collateral ligament (LUCL), 193–194, 200–201
- Lattisimus dorsi, 184–185, 318*f*, 319–320, 347
- Learning, defined, 454
- Legs, bipedalism, 490
- Levator scapulae muscle, 176
- Lever system, 531, 531*f*
  - components, 25
  - first class lever, 25, 26*f*
  - second class lever, 25–26, 26*f*
  - third class lever, 26, 27*f*
- Ligaments, 223–228, 287
  - architecture of, 134*f*
    - biomechanics and material properties, 133
    - composition and biochemical constituents, 132
    - function, 132–133, 138*f*
    - ligament healing, 135–136, 136*t*
    - mechanical loading and injury, 134–135
    - neural structures, 133
    - optimal loading and rehabilitation, 136–137
    - structure, 132, 138*f*
    - vascular supply, 133
  - carpal kinematics, effect of scaphoid excision on, 227
  - classification of, 224
  - defined, 115
  - extrinsic carpal ligaments, 224
  - of first carpometacarpal joint, 244–245
  - healing, 135–136, 136*t*
  - of Humphrey, 403–404
  - of hip joint, 376–377

    iliofemoral, 376
    ischiofemoral, 377
    ligamentum teres (foveal ligament), 376, 376*f*
    pubofemoral, 377
  innervation patterns of, 247
  intrinsic carpal ligaments, 227–228
  Madelung deformity, 225–227
  palmar extrinsic ligaments, 224–225
  proprioceptive function of, 223–224
  ulnocarpal complex, 228
  of Wrisberg, 403–404
Ligamentum nuchae, 315
Ligamentum teres (foveal ligament), 376, 376*f*, 385
Lim proteins, 64
Limbic loop, 445–446
Limbic system, 447
Limbus, 385
Limbus acetabuli, 375–376
Linburg–Comstock anomaly, 258
Lisfranc's joint, 421
Lister's tubercule, 217–218
Locomotor efficiency hypothesis, 489–490
Long-term memory, 456
Lordosis, 326, 330–332
Low-density lipoprotein (LDL), 141
Lower extremity muscles, 334
Lumbar disc herniation (LDH), 335
Lumbar discs, 325
Lumbar facet joints, 325
Lumbar flexion, 328–330
Lumbar lordosis, 491
Lumbar spine, 325–326, 329*f*, 330–332
Lumbar vertebral column
  facet joint, 330*f*
  functional anatomy, 325–326
  instantaneous axis of rotation, 334
  joint capsule and articular process, 331*f*
  kinematics of, 326–331
  kinetics of, 331–334
  in pathological conditions, 334–336
  sagittal alignment of spinal column, 330*f*
Lumbosacral joint, 343–344
  with iliolumbar ligaments, 344*f*
  spondylolysis and spondylolisthesis in, 345
Lumbrical muscles, 272–273, 433–434, 433*f*
Lunate, 216, 217*f*
  dislocation, 217–218
  Kienböck's disease, 218–219
  morphology, 217
  pathologies, 217–219
Lunatomalacia, 218–219
Lungs, 354–355
Lunotriquetral interosseous ligament (LTIL) injury, 217–218

M

Madelung deformity, 225–227
Madelung's disease, 213, 214*f*
Mandibular condyle, 285–286
Mandibular fossa, 285
Masseter muscle, 287
Mastication, 291–293, 292*f*
Mature bone (compact and spongy), 72–73, 72*f*, 73*f*
Maximum muscle power (MMP), 511–512
Mean arterial pressure (MAP), 366–367
Mechanical loading
  ligaments, 134–135
  tendon and ligament, 121–124, 140
Mechanical theory, 126
Mechanocoupling, 122–123
Mechanoreceptors, 33–34, 33*t*, 121, 151–152, 341, 375–376
Mechanotransduction, 121–124, 130
Medial and lateral retinaculum, 406
Medial collateral ligament (MCL), 193, 200–201, 206, 402, 404, 417, 417*f*
Medial condyles *vs.* lateral condyles, 394*t*
Medial longitudinal arch, 425, 425*f*, 432
Medial navicular tubercle, 414
Medial patellofemoral ligament (MPFL), 406
Medial pterygoid muscle, 288
Median nerve compression, 207
Median nerve injury, 249
  adductor pollicis, 249
Medio-lateral movement, 3, 4*f*
Medulla spinalis stimulates alpha motor neurons, 446
Memory, cognitive approaches, 456–457
Meningomyelocele, hip joint in, 387–388
Meniscus, 403–404, 404*f*
  medial *vs.* lateral meniscus, 404, 404*f*
Merchant's technique, 397
Metacarpals, 238–239
Metacarpophalangeal (MCP) joint, 220, 250–252
Metatarsal bones, 415
Metatarsophalangeal joints, 422–424, 424*f*, 432–434
  collateral ligaments of, 424*f*
  consist of, 422
  movement at, 427*f*
Midcarpal joint, 55, 221–222
Midfoot, 416
Mid-stance phase, human gait, 515–516, 516*f*
Mid-swing phase, human gait, 521, 522*f*, 523*f*
Midtarsal joint, 420–421, 421*f*, 422*f*, 423*f*
  movement at, 421, 423*f*
  oblique axis of, 423*f*
  plantar ligaments of, 422*f*
Migration Index, 387
Mirror neuron system, 462
Mixed type ataxia, 451
Modulation, 446
Monosodium urate monohydrate (MSU) crystal, 141
Mortis, tarsal bones, 413*f*
Mortise joint, ankle joint, 416
Motion
  abduction and adduction, 14, 14*f*
  analysis and motion capture technologies, 317–318
  assessments, range of, 255–256
  definition, 15
  diagnosis, movement disorders, 15
  flexion and extension, 14, 15*f*
  kinematic parameters, 15
  kinetic parameters, 15
  measurements, documentation of range of, 256
  net force, 15
  rotational/angular movement, 15
  spatial and temporal parameters, 15
  translational/linear motion, 15
  values, normative range of, 256
Motor adaptation, 458
Motor control and sensory-motor integration of human movement
  closed- loop, 448
  cognitive loop, 445–446
  in different life stages, 446–448
  disabilities and pathological conditions, 450–451
  gait, 450*f*
  gravity, 448–449
  limbic loop, 445–446
  linear force, 449
    external forces, 449
    internal forces, 449
  motor control, defined, 443
  motor loop, 445–446
  neuroanatomy and neurophysiology, 443
  oculomotor loop, 445–446
  open-loop, 448
  physiological basis of, 443
  prefrontal loop, 445–446
  rotatory force, 449
  sensory-motor feedback and perception of movement, 443–446
    sensory inputs, 444–445
    sensory systems, 443–444
  torque, 449
Motor learning, 7, 454*f*
  defined, 453
  disability of, 461
  in expertise, 460–461
  learning hypotheses, 453–458
    behavioral approach, 454–455
    cognitive approaches, 455–457
    ecological theory, 453
    physiological approach, 457–458
    Schmidt's schema theory of discrete motor skill learning, 453
  learning skill in different life stages, 459–461
  myelination, 460
  in rehabilitation, 461–463
  stages of, 458–459
    Bernstein's three-stage model, 459
    Fitts and Posner three-stage model, 459
    good and bad variance, 459
    Halsband's model, 459
  types of, 453
Motor loop, 445–446
Motor memory, 456
Motor movement, 447–448
Motor skill, defined, 453
Movements of hip joint, 380
  anteversion angle, 380–381, 381*f*

Movements of hip joint (*Continued*)
  femoral movements on pelvis, 381–382, 381*f*, 382*f*
  hip joint, walking and running, 383–384
  inclination angle, 380
  pelvis movements on femur, 382–383, 382*f*, 383*f*
  proprioceptive and kinesthetic issues of hip region, 384
Msx gene, 64
Multifidi muscles, 315–316, 320, 332
Multiple sclerosis (MS), 451, 472
Multisensory integration, 480, 481*f*
Muscle disorders, TMD related to, 295–296
Muscle tissue
  architecture, 101, 104–105, 105*f*
  fiber type distribution, 101
  life stages, 108
  mechanical properties
    length-tension relationship, 105, 106*f*
    pelvic floor, 107–108
    shoulder, 107, 107*t*
    trunk, 107
    upper limb, 106–107
  microstructure
    actin monomers, 103
    basal lamina, 102
    connective tissue layers, 102, 102*f*
    contractile segment, 101–102
    desmin, 104
    endomysium, 102
    myofibrils, 102
    myosin, 103
    sarcomeres, 101, 103, 104*f*
    sarcoplasm, 101–102
  pathological conditions
    denervation, 108
    immobilization, 109
    spasticity, 108–109
  rehabilitation approach
    neuromuscular electrical stimulation (NMES), 110–111
    strengthening, 110
    stretching, 109–110
    tendon transfers, 111
Muscles, 233–235, 248–252, 287–289
  ankle and foot complex, 427–435
    anterior muscles, 427–428, 427*f*
    dorsal intrinsic muscles, 434–435
    lateral group muscles, 430–431
    plantar intrinsic muscles, 431–434
    posterior muscles, 428–430, 428*f*
  Bennett fracture, 250, 251*f*
  dynamic stabilization of the first carpometacarpal joint, 250
  extrinsic extensor muscles, 233
  Froment sign, 249–250, 249*f*
    abductor pollicis longus (APL), 249
    extensor pollicis brevis, 249–250
    extensor pollicis longus, 250
    first dorsal interosseous, 250
  infrahyoidal muscles, 289
  lateral pterygoid muscle, 288–289
  masseter muscle, 287
  medial pterygoid muscle, 288
  median nerve injury, 249
    adductor pollicis, 249
  metacarpophalangeal joints of the fingers, 250–252
  osteoarthritis, 252
  proprioceptive function of the ligaments, 233
  suprahyoidal muscles, 289
  temporalis muscle, 287–288
  thenar muscles, 248–249, 248*f*
    abductor pollicis brevis, 248
    flexor pollicis brevis (FPB), 248
    opponens pollicis (OP), 248–249
  wrist extensor muscles, 233–234
    extensor carpi radialis longus and brevis muscles, 233–234
    extensor carpi ulnaris muscle, 234
  wrist flexor muscles, 234–235
    flexor carpi radialis muscle, 235
    flexor carpi ulnaris muscle, 234–235
    palmaris longus muscle, 235
Muscles of shoulder complex, 174–185
  distal mobilizers, 179–185
    arm adductors, 184
    arm elevators, 180–184
    arm rotators, 184
    axiohumeral muscles, 184–185
    latissimus dorsi muscle, 184–185
    pectoralis major muscle, 184, 185*f*
  proximal stabilizers, 174–179
    scapulothoracic joint abductors, 178–179
    scapulothoracic joint adductors, 178
    trapezius muscle (upper portion), 174–178
Muscle trigger points, 153
Muscular activation, 21, 21*f*
Musculoskeletal and movement adaptations, 478–479
Musculoskeletal system, forces, 22, 22*f*
Myofascial trigger point, 153

N

National Space Biomedical Research Institute (NSBRI), 477
Navicular, tarsal bones, 414, 415*f*
Neovascularization, 125–126, 130–131
Nerve growth factor (NGF), 135–136
Neural adaptation, 133
Neural control mechanisms, reflex and purposeful movements
  aggregate field theory, 29–30
  central nervous system, 29. *See also* Central nervous system
  integrative scheme of, 30, 30*f*
  peripheral nervous system, 29. *See also* Peripheral nervous system
  phrenology theory, 29
  sensory feedback systems, 29–30
  stimulating agents, 29
Neural networks, 457–458
Neural theory, 126
Neuromodulation, 446
Neuromuscular disorders, 384
Neuromuscular electrical stimulation (NMES), 110–111
Neuromuscular hip, 384
Neuroplasticity, 455–456, 462–463
Newtonian mechanics, 3–4
Newton's first law, 25
Newton's Laws of Motion, 366, 532
Newton's second law, 25
Newton's third law, 25
NI. *See* Normally index (NI)
Nociceptors, 121, 341, 375–376
Nonassociative learning, 455
Non-fibrillar organic matrix, 76–77
Nonspecific low back pain (NSLBP), 472–473
Nonsteroidal anti-inflammatory drugs (NSAIDs), 130, 142, 348
Normally index (NI), 7
Notochord, 61–63

O

Obesity, 141
Observational gait analysis (OGA), 506, 507*t*
  defined, 506
  Edinburgh Visual Gait Analysis system, 506
  marked abnormalities, 506
  moderate abnormalities, 506
  normal movement, 506
  recorded video, 506
  reliability and validity of, 506, 507*t*
Observational learning, 455–456, 462
Obstructive lung diseases, 361, 361*t*
Obturator externus muscle, 378
Obturator internus muscle, 378
Oculomotor loop, 445–446
Ohm's law, 370
Olecranon, 192
Olecranon bursitis, 207
Olecranon stress fracture, 207
Open kinetic chain exercises, 535–536, 535*f*
Open-loop, 448
Open skills, 459
Open reduction and internal fixation (ORIF), 346–347
Operant conditioning, associative learning, 455
Opponens digiti minimi (ODM), 220
Opponens pollicis (OP), 219, 248–249
Opposition kinematics of first carpometacarpal joint, 244
Optimal loading, 130–131, 136–137
Organic extracellular matrix, 76–77
Osteitis pubis, 348
Osteoarthritis (OA), 56, 86, 87*f*, 97–98, 243, 252, 388–389
Osteoblasts, 74–75, 74*f*
Osteochondritis dissecans (OCD) of capitellum, 206
Osteoclastogenesis, 84–85
Osteoclasts, 75–76
Osteocytes, 75, 84
Osteogenesis imperfecta (OI), 86–87
Osteokinematics, 18, 52, 174, 289–290
  depression and elevation, 290
  of femur/pelvis, 381
  lateral excursion, 290

  protrusion and retrusion, 290
  of tibiofemoral joint, 396*f*
Osteolysis and mineralization, 85
Osteomyelitis, 86
Osteophytic spikes, 321
Osteoporosis (OP), 86, 375

P

Pacini type mechanoreceptors, 384
Palmar aponeurosis, mechanical analysis of, 261
Palmar aponeurosis pulley, 261
Palmar extrinsic ligaments, 224–225
Palmar interosseal muscles, 273
Palmaris longus muscle, 235
Panner disease. *See* osteochondritis dissecans (OCD) of capitellum
Paratendonitis, 124
Paratenonitis, 125*t*
Paravertebral muscles, 326, 331–332
Parkinson disease (PD), 450–451, 462, 472
Pascal law, 366
Passive range of motion (PROM), 255
Patella, 396, 397*f*
Patella alta, 398
Patellar contact area, 399*f*
Patellar stability, 398
Patellar tendinopathy, 125*f*
Patellar tilt angle, 397
Patellar tracking, 397–398
Patellofemoral contact area, 398, 399*f*
Patellofemoral joint, knee joint, 396–399
  normal alignment *vs.* malalignment, 397–398
  patella, 396, 397*f*
  patellofemoral contact area, 398, 399*f*
  patellofemoral joint stress, 399
  patellofemoral motion, flexion and extension, 398
  patellofemoral reaction force (PFRF), 399, 399*f*
  restraints, 406
    iliotibial tract (ITT), 406
    medial and lateral retinaculum, 406
    medial patellofemoral ligament (MPFL), 406
  trochlear groove, 396–397, 397*f*
Patellofemoral joint stress (PFJS), 399
  in weight bearing *vs.* non-weight bearing, 399
Patellofemoral motion, 398
Patellofemoral pain syndrome, 397–398
Patellofemoral reaction force (PFRF), 399, 399*f*
Pax gene, 64
Pectoralis major muscle, 184
Pectoralis minor muscle, 177–178, 185*f*
Pelvic deltoid muscle, 379
Pelvic fractures, 346
Pelvic obliqueness, 388
Pelvic rotation, 335
Pelvis, 339
  bipedalism, evolution of, 492–493, 493*f*
  bones of, 340–341
    acetabulum, 341
    ilium, 340
    ischium, 340
    pubis, 340
  femoral movements on, 346, 381–382, 381*f*, 382*f*
  motion during human gait, 345–346
  motions on femur, 344–345, 382–383, 382*f*, 383*f*
    frontal plane, movements in, 344
    horizontal plane, movements in, 345
    lumbopelvic rhythm, 345
    sacroiliac joint, movements in, 345
    sagittal plane, movements in, 344
  pathomechanics in orthopedic conditions, 346–348
    acetabular dysplasia, 347
    acetabular fractures, 347
    external fixation, 346–347
    osteitis pubis, 348
    pelvic fractures, 346
    sacroiliac joint dysfunction (SIJD), 347–348
    spondylolisthesis, 348
    spondylolysis, 348
  pelvic floor muscles, 340*f*
  pelvis-related joints, 341–344
    hip joint, 343
    lumbosacral joint, 343–344
    sacroiliac joint, 342
    symphysis pubis, 342–343
Pelvis-lumbar-thoracic model, 335
Pemberton or Chiari osteotomy, 387–388
Perceptual learning, 455
Perilunate dislocations, 231
Peripheral nervous system
  autonomic nervous system, 31–32
  components, 31
  Golgi tendon organs, 34
  joint receptors, 34
  mechanoreceptors, 33–34, 33*t*
  motor systems
    automatic behaviors, 35
    movements, classification, 34, 35*t*
    reflex pathways, 34–35
  muscle spindles, 34, 34*t*
  neurons, 32, 32*t*
  proprioceptive receptors, 34
  somatosensory systems, 32–33
  synapses, 32
Peripheral neuropathy, 449
Peritendinitis, 124
Peroneal muscles, 517
Peroneus brevis, 431
Peroneus longus muscle, 430–431
Peroneus tertius, 428
Peroxiredoxin 5, 126
Pes anserinus, 402, 403*f*
Pes equinovarus deformity, 429–430
Pes varus, 429–430
Phalanges, 238–240, 241*f*, 416
Phrenology theory, 29
Phylogenetic memory, 459–460
Physical adaptation, weightlessness on human body, 477–478
Physical education, 8
Physiological approach, motor learning
  acquisition and retention of motor skill, 457
  motor adaptation, 458
  neural networks, 457–458
  serial reaction time (SRT) task, 457
Physiological cross sectional area (PCSA), 104–105
Piriformis muscle, 377–378
Pisiform, 219
Pivot joint, 48–49, 49*f*
Plane joint, 50, 50*f*
Plantar fascia, 426, 426*f*
Plantar fasciitis, 152
Plantar flexors, 514, 520
Plantar interosseal muscles, 434, 434*f*
Plantar intrinsic muscles, 431–434, 432*f*
  abductor digiti minimi, 433
  abductor hallucis muscle, 432
  adductor hallucis, 433
  dorsal interosseal muscles, 434, 434*f*
  flexor digiti minimi brevis, 433
  flexor digitorum brevis, 432–433
  flexor hallucis brevis, 432
  lumbrical muscles, 433–434, 433*f*
  plantar interosseal muscles, 434, 434*f*
  quadratus plantae, 433
Plantar pressure analysis, 509–510, 510*f*, 511*f*
Plantaris, 429
Plantaris muscles, ankle and foot complex, 428
Plasticity, 140, 456
Platelet-rich plasma (PRP), 142
Poiseuille law, 369
Popliteus, 402
Posterior bundle of medial collateral ligament (PMCL), 193
Posterior cruciate ligament (PCL), 405, 405*f*
Posterior dysfunction, SID, 347
Posterior hip, 378*f*
Posterior interosseous nerve (PIN), 206
Posterior longitudinal ligament, 315
Posterior meniscofemoral ligament, 403–404
Posterior muscles, 428–430, 428*f*
  flexor digitorum longus, 430
  flexor hallucis longus, 430
  gastrocnemius, 428–429
  plantaris, 429
  soleus, 429
  tibialis posterior, 429–430
Posterior oblique ligament (POL), 244
Posterior olecranon impingement, 207
Posterior pelvic tilt, 383, 383*f*
Posterior sacroiliac ligaments, 342, 343*t*
Posterior superior iliac spines (PSIS), 345
Posterior talofibular ligaments, 417–418
Posterolateral corner (PLC) restraints, 406
Posterolateral (PL) bundles, 405
Posterolateral rotatory instability (PLRI), 202*f*
Posteromedial (PM) bundles, 405
Postmenopausal osteoporosis, 478
Postural control. *See also* Balance and postural control
  integrative models to, 468–469
  models of, 469

Postural control (*Continued*)
  multisensory integration for, 481*f*
Postural feeding hypothesis, 490
Posturography, 470
POU gene, 64
Power, 36
Prefrontal cortex, 445–446
Prefrontal loop, 445–446
Premotor cortex, 445
Pre-swing phase, human gait, 518–520, 519*f*, 520*f*
Primary and accessory muscles, 358*t*
Primary tensile load system, 414
Principal component analysis (PCA), 388
Principles
  anatomy, 13
  ankle joints, 14
  biomechanics, 13
  cardinal axes and planes, 13, 14*f*
  equilibrium, 26–27
  internal and external rotation movements, 13, 14*f*
  kinematics, 13. *See also* Kinematics
  kinetics, 13. *See also* Kinetics
  levers
    components, 25
    external and internal forces, 25
    first class lever, 25, 26*f*
    second class lever, 25–26, 26*f*
    third class lever, 26, 27*f*
  mathematical fundamentals
    biomechanical measurements, units, 16, 16*t*
    physical quantities, 16
    scalar quantities, 16
    trigonometric functions, 17, 17*f*
    vector analysis, 16–17, 17*f*
    vector quantities, 16
  motion. *See* Motion
  Newton's laws, 25
  physiology, 13
  transverse plane, 13
Procedural deficit hypothesis, 461
Procedural learning, 454
Procedural memory, 456
Progressive mechanical loading, 136–137
Proliferation phase, tendon healing, 127–129, 129*t*
Pronation, 196–197
Pronator teres, 198
Proprioception, 151–152, 151*f*
Proprioceptive and kinesthetic issues of hip region, 384
Proprioceptive function of ligaments, 223–224, 233
Proprioceptive receptors, 34
Proteoglycans, 132
Protraction, 161
Protrusion and retrusion, 290–291
Proximal femur fractures, 389
Proximal junctional kyphosis, 321
Proximal radioulnar joint (PRUJ), 192
Proximal stabilizers, 174–179
  axioscapular and axioclavicular muscles, 174–179
  scapulothoracic joint abductors, 178–179
  scapulothoracic joint adductors, 178
  trapezius muscle (upper portion), 174–178
Proximal tibia, articular surface of, 394*f*
Proximal tibiofibular joint, 416
Proximal-mid humerus, 159–160, 159*f*
Pseudotumor, 321
Psoas major muscle, 326, 332–333, 378
Psoas minor, 333
Psoas muscles, 335–336
Pubic spring test, 348
Pubis, 340
Pubofemoral ligament, 377
Pulleys, 22
Pulvinar, 385

Q

Quadratus femoris muscle, 378
Quadratus lumborum muscle, 333
Quadratus plantae, 433
Quadriceps femoris, 399, 400*f*
  function of, 400–401
Quadriceps (Q) angle, 401
  defined, 401
  dynamic Q angle, 401
  supine *vs.* standing, 401
  women *vs.* male, 401
Quadriga phenomenon, 257
Quiet expiration, 358

R

Radial and ulnar deviation, 232
Radial collateral ligament (RCL), 193–194, 225
Radiocarpal and the midcarpal motion, 228
Radiocarpal joint, 221
Radioscapholunate (RSL) fusion, 236
RCIG. *See* Royal Central Institute of Gymnastics (RCIG)
Reactive tendinopathy, 126
Rearfoot, 416
Rectus abdominis muscle, 326, 333
Rectus femoris muscle, 399–401, 400*f*, 514, 518–520
Reflector markers, 507
Rehabilitation, 130–131, 131*t*, 137, 347
  fascia, 151, 153
  motor learning, 461–463
  tendon and ligaments, 136–137
Relative motion concept, 270–271
Relaxin, 139–140
Remodeling phase, tendon healing, 127–130, 129*t*
Ramus ossis, 340
Renaissance, 3
Renal disease, 141–142
Repetitive transcranial magnetic stimulation (rTMS), 457
Resistive force, 531
Respiration, 353
  anatomical differences, infants and adults, 360*t*
  conducting airways and alveoli, 353–354, 355*f*
  control of respiration, 354*f*
  in different life stages, 359–360
  lungs, 354–355
  mechanics of, 358–359
  muscle of, 357*f*
  muscular actions, ventilation, 356–358
    expiratory muscles, 358
    inspiratory muscles, 356–358
  pathomechanics of, 360–362
    obstructive lung diseases, 361
    restrictive lung dysfunction, 361–362
  physiological differences, infants and adults, 360*t*
  primary and accessory muscles of, 358*t*
  rib and spinal column, 356*f*
  rib movement, inspiration, 357*f*
  thoracic cage, 355–356, 356*f*
  thorax, structure of, 353–359
  upper airways, 354*f*
Respiratory distress syndrome (RDS), 359
Resting Energy Expenditure (REE), 40
Restrictive lung dysfunction, 361–362
Resultant force, 20, 21*f*
Reticulospinal tract, 445
Retinacular ligaments, 267–268
Retraction, 161
Reynolds number, 370
Rheumatoid arthritis (RA), 56
Rhomboid major and minor muscles, 176
Rhomboid muscles, 320
Rhythmic and automatic behaviors, 29
Rib hump, 322
Ribs, 315
Robot-assisted therapy, 461–462
Roman foot, 415
Root mean square (RMS) amplitude, 471–472
Root mean square (RMS) velocity, 471–472
Rotation
  downward, 166
  internal, 166
  sacroiliac joint, 331
  upward, 166
Royal Central Institute of Gymnastics (RCIG), 8
Ruffini type mechanoreceptors, 384

S

Sacroiliac joints (SIJ), 326, 331, 331*f*, 332*f*, 342
  anterior, 342*f*
  ligaments of, 343*t*
  movement of, 345
  posterior, 342*f*
Sacroiliac joint dysfunction (SIJD), 336, 347–348
Sacrospinous ligament, 332, 342, 343*t*
Sacrotuberous ligament, 332, 343*t*
Sacro-tuberous and sacro-spinous ligaments, 331
Sacrum, bipedalism, 491–492

Saddle joint, 49, 49*f*
Sagittal band injury, 266–267
Scaphoid, 215–216
  excision effecet on carpal kinematics, 227
  fractures, 216
Scapholunate instability, carpal kinematics following, 235–236
Scapholunate interosseous ligament (SLIL) injury, 217–218
Scaphotrapeziotrapezoidal (STT) joint, 215–216
Scapula, 157–159, 158*f*, 166
Scapular dyskinesis, 159
Scapular kinematics, 534*f*
Scapular winging, 179
Scapulohumeral muscles, 179–185
  arm adductors, 184
    deltoid muscle, 181*f*, 184
    teres major muscle, 184
  arm elevators, 180–184
    biceps brachii, 182–183
    coracobrachialis muscle, 182
    deltoid muscle, 180–181, 181*f*
    infraspinatus muscle, 183
    subscapularis muscle, 183–184
    supraspinatus muscle, 181–182
    teres minor muscle, 183
  arm rotators, 184
  axiohumeral muscles, 184–185
  latissimus dorsi muscle, 184–185
  pectoralis major muscle, 184
Scapulohumeral rhythm, 171–173
Scapulothoracic joint, 163–166, 165*f*, 166*f*, 178–179
  abductors, 178–179
  adductors, 178
  serratus anterior muscle, 178–179, 179*f*
  trapezius muscle, 178
  kinematics, 163–166
Schmidt's schema theory, 453, 461
Schmorl's nodes, 321–322, 334
Scientific Advisory Committee, 8
Scoliosis, 322
Screw-home (locking) mechanism, 395–396, 517–518
Seed eating hypothesis, 490
Semantic memory, 456
Sensory-compensation, 479–480
  center of mass (COM), 480–481
  and cognitive functions, 482
  sensory integration, 480
  sensory weighting, 480–481
Sensory feedback systems, 29–30
Sensory integration, 446, 480, 481*f*
Sensory-motor integration, 479
  of balance and postural control, 469
  closed- loop, 448
  cognitive loop, 445–446
  in different life stages, 446–448
  disabilities and pathological conditions, 450–451
  gait, 450*f*
  gravity, 448–449
  limbic loop, 445–446
  linear force, 449
    external forces, 449
    internal forces, 449
  motor control, defined, 443
  motor loop, 445–446
  neuroanatomy and neurophysiology, 443
  oculomotor loop, 445–446
  open-loop, 448
  physiological basis of, 443
  prefrontal loop, 445–446
  rotatory force, 449
  sensory-motor feedback and perception of movement, 443–446
    sensory inputs, 444–445
    sensory systems, 443–444
  torque, 449
Sensory organization test (SOT), 480–481
Sensory weighting, 480–481
Seratonergic neurons, 444
Serial reaction time (SRT) task, 457
Serotonin, 371
Serratus anterior muscle, 178–179, 179*f*
Serratus posterior muscle, 320
Sesamoid bones, 220, 425
Shear forces, 23
Shear stress, 366, 370
Short-term memory, 456
Shoulder complex, kinesiology of, 155
  bones of the shoulder complex, 157–160
    clavicle, 157, 162*f*, 173*f*
    proximal-mid humerus, 159–160, 159*f*
    scapula, 157–159, 158*f*
    sternum, 160
  joints of shoulder complex, 160–174
    acromioclavicular joint, 162–163, 163*f*, 164*f*
    glenohumeral joint, 167–174, 167*f*, 169*f*, 170*f*, 171*f*
    scapulothoracic joint, 163–166, 165*f*, 166*f*
    sternoclavicular joint, 160–162, 161*f*
  muscles of shoulder complex, 174–185
    distal mobilizers, 179–185
    proximal stabilizers, 174–179
Shoulder external rotation, arthrokinematics during, 173*f*
Shoulder girdle
  movement of, 157
  primary function of, 157
Shoulder joint, 55
Skull, bipedalism, 490, 492*f*
Skylab missions, 481
Sliding hip screw (SHS), 389
Sling lying hip abduction exercise, 529, 530*f*
6-minute walk test, 508–509
Small-object feeding hypothesis, 490
Social display hypothesis, 489
Soleus, 428–429, 515–517
Somato-sensory cortex, 481–482
Somatosensory system, 32–33, 479, 481–482
Space motion sickness (SMS), 477
Space-flight studies, 478
Spasmatic paraspinal muscles, 335
Spastic hip dysplasia, 387*t*
  vs. developmental hip dysplasia, 386, 387*t*
Spastic hip flexors, 386–387
Specific Adaptation to Imposed Demand (SAID) principle, 535
Spina bifida (SB), 387–388
Spinal instability, 335
Spine, bipedalism, 490–491, 492*f*
Spondylolisthesis, 335–336, 348
Spondylolysis, 335–336, 348
Squat exercise, 536
Stabile and mobile columns, grip activities, 240–241
Stabilogram, 470
Starling's Law, 365, 367–368
Static compliance, 359
Static stability, 169
Stener lesion, 246, 247*f*
Stenosing tenosynovitis, 125*t*
Sternoclavicular joint, 160–162, 161*f*
Steroids, 142
Sternum, 160
Stiffness, fascia, 152
Strength training, 131
Stress, 366
Stress reflex, 455
Stress-relaxation test, 119–120
Stretch reflex, 455
Stroke, 472
Subacromial impingement syndrome, 171–173
Subclavius muscle, 178
Sub-phases, human gait, 511, 512*f*, 512*t*
Subscapularis muscle, 183–184
Subserous fascia, 149–150
Substantia nigra compact, 450–451
Subtalar joint, 54, 419–420, 420*f*
Sulcus angle, 397, 397*f*
Superficial fascia, 149–150
Supertendon, 117–118
Supination, 196–197
Supinator muscle, 198–199
Suprahyoidal muscles, 289
Supraspinatus muscle, 169–170, 181–182
Supraspinatus tendon, 127*f*
Supraspinous ligaments, 315
Surfactant, 359
Surveillance systems, 9–10
Swan neck deformity, 268–270
Sway path, defined, 471
Symphysis pubis, 342–343
Synapses, 32
Synarthrosis, 47
Syndetome, 61–62
Synovial bursa, 170
Synovial fluid, 50
Synovial joint
  biaxial joints, 51
  degree of freedom (DOF), 51, 51*f*
  frontal plane, 50–51
  multiaxial joint, 51
  nonaxial joint, 51
  of rotation, 50–51, 51*f*
  sagittal plane, 50–51
  sub-classification, 51–52

Synovial joint (*Continued*)
  transverse plane, 50–51
  uniaxial joint, 51
Synovial tendon sheaths, 116

T

Talar dome, 412–413
Talonavicular ligament, 420
Talus, tarsal bones, 412–413
Tarsal bones, 412–415
  calcaneus, 413–414, 414*f*
  cuboid, 415
  cuneiforms, 414–415, 415*f*
  mortis, 413*f*
  navicular, 414, 415*f*
  talar surfaces and tibio-talar joint axis, 413*f*
  talus, 412–413
Tarsometatarsal joints, 421–422, 424*f*
T-box (Tbx) gene, 65
TEE. *See* Total Energy Expenditure (TEE)
TEF. *See* Thermic Effect of Food (TEF)
Temporalis muscle, 287–288
Temporomandibular dysfunction (TMD), 293–294
  disc derangements, 296–298
    disc displacement with reduction (DDwR), 296–297, 297*f*
    disc displacement without reduction (DDwoR), 297–298, 298*f*
  muscle disorders, 295–296
  TMJ arthralgia, arthritis, and arthrosis, 298–299
Temporomandibular joint (TMJ), 283, 286*f*, 289, 291*f*, 298–299
  kinematics of, 289–293
    arthrokinematics, 290–293
    osteokinematics, 289–290
  kinetics of, 293–295
    mechanical loading in the articular disc, 294–295
    mechanical loading in the TMJ, 294
    muscle activation and stabilization of the TMJ, 293–294
  mechanical loading in, 294
  muscle activation and stabilization of, 293–294
  pathomechanics of, 295–299
    disc derangements, TMDs related to, 296–298
    muscle disorders, TMDs related to, 295–296
    TMJ arthralgia, arthritis, and arthrosis, TMDs related to, 298–299
  structure of, 285–289
    articular disc, 286
    capsules, 286–287
    innervation, 289
    ligaments, 287
    mandibular condyle, 285–286
    mandibular fossa, 285
    muscles, 287–289
Tenascin-C, 117
Tendinopathy, 124–126
Tendinosis, 124, 125*t*
Tendinous failure, 141–142
Tendon and ligament, 115, 122*f*, 137–138
  adaptation concept, 121–124
  affecting factors for the architectures of, 138–142
    aging, 138–139
    connective tissue disorders, 142
    diabetes mellitus, 141
    gender and hormones, 139–140
    hypercholesterolemia, 141
    hyperuricemia, 141
    immobilization, disuse and exercise effects, 140–141
    obesity, 141
    pharmacologic agents, 142
    reconstruction and tissue engineering, 142
    renal disease, 141–142
  architecture of ligaments, 134*f*
    biomechanics and material properties, 133
    composition and biochemical constituents, 132
    function, 132–133, 138*f*
    ligament healing, 135–136, 136*t*
    mechanical loading and injury, 134–135
    neural structures, 133
    optimal loading and rehabilitation, 136–137
    structure, 132, 138*f*
    vascular supply, 133
  biomechanics and mechanical properties, 118–120
  composition and biochemical constituents, 117
  creep response, 120*f*
  function, 117–118, 138*f*
  injury and pathology, 124–127, 125*t*
    acute ruptures, 124
    chronic degenerative tendinopathies, 124
    optimal loading, 130–131
    rehabilitation, 130–131, 131*t*
    tendinopathy, 124–126
    tendon healing, 127–130, 128*f*, 129*t*
    tendon rupture, 126–127, 127*f*, 128*f*
  load–elongation curve, 119*f*
  load relaxation graph, 120*f*
  mechanical loading, 121–124, 140
  mechanical properties, 138*f*
  neural structures, 121
  patellar tendon and anterior cruciate ligament, 116*f*
  physiological responses to mechanical loading and injury, 121
  stress–strain curve, 118, 119*f*
  structure, 115–117, 116*f*, 138*f*
  vascular supply, 120–121
Tendon disrepair phase, 126
Tendon healing, 127–130, 128*f*, 129*t*
Tendon rupture, 126–127, 127*f*, 128*f*
Tenoblasts, 115
Tenocytes, 115
Tenosynovitis, 124, 125*t*
Tensegrity, 123
Tensile forces, 23
Tensor fascia lata muscle, 379
Teres major muscle, 184
Teres minor muscle, 183
Terminal stance phase, human gait, 516–518, 518*f*, 519*f*
Terminal swing phase, human gait, 521–524, 523*f*, 524*f*
Terrestrial locomotion, 36–37
Thalamic fibers, 445
Thenar muscles, 248–249, 248*f*
  abductor pollicis brevis, 248
  flexor pollicis brevis (FPB), 248
  opponens pollicis (OP), 248–249
Thermal radiation avoidance hypothesis, 489–490
Thermic Effect of Food (TEF), 40
Thoracic cage, 355–356, 356*f*
Thoracic kyphosis, 315, 319–322, 334
Thoracic vertebral column, 315
  functional anatomy, 315–316, 316*f*
  instantaneous axis of rotation, 320
  kinematics of, 317–319
  kinetics of, 319–320
  in pathological conditions, 321–322
Thorax, scapular motion on, 166*f*
3-Dimensional gait laboratory, 7
Thrombospondin, 94
Thumb
  carpometacarpal joint of, 241–242
  flexor tendon sheath, 262
  distribution of the forces on the joints of, 242–243
  flexor pulley system of, 263*f*
  movements of, 243*f*
  opposition, measurement of, 244
  osteoarthritis of carpometacarpal joint of, 243
Thyroid hormones, 140
Tibia, 420, 495, 514
Tibial plateau, 393
Tibial torsion measurement, 411, 412*f*
Tibialis anterior, 427, 521–522
Tibialis posterior, 429–430, 517
Tibiofemoral joint, 54–55, 393–396, 394*f*, 394*t*
  distal femur, articular surface of, 394*f*
  knee joint, 393–396, 394*f*, 394*t*
    distal femur, articular surface of, 394*f*
    lateral condyles vs. medial condyles, 394*t*
    motions, 394–395
    normal alignment vs. malalignment, 393–394
    proximal tibia, articular surface of, 394*f*
    screw-home (locking) mechanism, 395–396, 396*f*
  lateral condyles *vs.* medial condyles, 394*t*
  motions, 394–395
  normal alignment *vs.* malalignment, 393–394
    frontal plane, 393–394
    sagittal plane, 394, 395*f*, 396*f*
  passive static restraints, 403–406
    collateral ligaments, 404
    cruciate ligaments, 404–405, 405*f*
    knee joint capsule, 403

    meniscus, 403–404, 404*f*
    patellofemoral joint restraints, 406
    posterolateral corner (PLC) restraints, 406
  proximal tibia, articular surface of, 394*f*
  screw-home (locking) mechanism, 395–396
Tissue engineering, 142
Toes, bipedalism, 495–496, 495*f*
Tool-use hypothesis, 489
Torque, 23, 36, 449, 532
Torsional force, 23
Total active motion (TAM), 255
Total Energy Expenditure (TEE), 40
Total passive motion (TPM), 255
Total rotational motion (TROM), 174
Trabecular bony scaffolds, 325, 326*f*
Transforming growth factor (TGF)-β, 65
Transvers arch (TSA), 425–426, 425*f*
Transversus abdominis muscle, 333–334
Trapezius muscle, 174–178, 219
  levator scapulae muscle, 176
  pectoralis minor muscle, 177–178, 185*f*
  rhomboid major and minor muscles, 176
  subclavius muscle, 178
  trapezius muscle (lower portion), 176–177
Trial-and-error learning, 455
Triangular fibrocartilage complex (TFCC), 212–213, 221, 232
Triceps brachii, 198, 201*f*
Triceps Surae, 428
Triceps tendon rupture, 207
Trigger points, fascia, 153
Triquetrum, 219
Trochlea, 412–413
Trochlear dysplasia, 396–397
Trochlear groove, 396–397, 397*f*
Tropocollagen, 117
Trunk flexion thoracic vertebrae, 319
Tumoral calcification, 321
Two-dimensional optoelectronic measurement system, 318
Two-layered joint capsule, 50
Type I collagen, 117, 127–129, 132
Type II collagen, 94, 96–97
Type III collagen, 117, 127–129

U

Ulnar collateral ligament (UCL), 245–246
Ulnar neuropathy, 205
Ulnar variance, on wrist biomechanics, 213
Ulnocarpal complex, 228
Uncovertebral joint of Luschka, 304
Uner Tan Syndrome, 490
Upper airways, 354*f*
Upward rotation, 166

V

Valgus-extension overload syndrome, 205
Vascular supply, 120–121, 133
Vascular theory, 126
Vastus lateralis *vs.* vastus medialis, 399–400, 400*f*
Vastus medialis obliquus (VMO), 400
Venoconstriction, 369–370
Ventilation, muscular actions, 356–358
  expiratory muscles, 358
  inspiratory muscles, 356–358
Vestibular cortex, 479
Vestibullar ataxia, 451
Visual system, 443–444
Volar intercalated segment instability (VISI), 217–218
Volar plate injury, 254

W

Waddling gait, 348
Walking cycle, 3, 5*f*
Wall press exercise, 532*f*
Waterfalls phenomena, 369
Weighted biceps curl exercise, 535*f*
Weightlessness on human body, effects of
  musculoskeletal and movement adaptations, 478–479
  physical adaptation, 477–478
  sensory-compensation, 479–480
    center of mass (COM), 480–481
    and cognitive functions, 482
    sensory integration, 480
    sensory weighting, 480–481
  spatial orientation, 479
Windlass mechanism, 427*f*
Wnt family, 65
Work, 36
Work of breathing (WOB), 358
Working memory, 456
Wrist, kinesiology of, 211–236
  artrology, 220–236
    articulations, 221–223
    carpal kinematics, 228–231
    carpal motions during wrist movements, 231–232
    kinesiology in various carpal conditions, 235–236
    ligaments, 223–228
    muscles, 233–235
    wrist joint structure, 220–221
  osteology, 211–220
    carpal bones, 213–220
    distal radius, 211–212
    distal ulna, 212–213
    sesamoid bones, 220
Wrist arthrodesis position, 229
Wrist extensor muscles, 233–234
  extensor carpi radialis longus and brevis muscles, 233–234
  extensor carpi ulnaris muscle, 234
Wrist flexor muscles, 234–235
  flexor carpi radialis muscle, 235
  flexor carpi ulnaris muscle, 234–235
  palmaris longus muscle, 235
Wrist joint structure, 220–221
Wrist rhythm, 230

Z

Zinc finger transcription factors, 65

Comparative Kinesiology of the Human Body

Normal and Pathological Conditions

Edited by

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Comparative Kinesiology of the Human Body: Normal and Pathological Conditions covers the changes in musculoskeletal, neurological and cardiopulmonary systems, which are the three pillars of human movement. It examines the causes, processes, consequences, and contexts of physical activity from different perspectives and in different life stages including early childhood to elderly. It goes on to further explain how purposeful movement of the human body is affected by pathological conditions related to any of these major systems. Coverage also includes external and internal factors (such as forces and other stresses) that affect the human growth pattern and development, and throughout lifespan (embryo, child, adult, and geriatrics). The perfect reference for researchers of kinesiology as well as clinicians and students involved in rehabilitation practice.

KEY FEATURES

- Explores the three pillars of human activity: the musculoskeletal system as the body segments where and how motion occurs; the neurological system as the sensory-motor control of human movement; and the cardio-pulmonary system as the source of energy supply for the moving body
- Includes in depth coverage of the mechanical behavior of the embryo as one of the major determinants of human movement throughout the life cycle
- Provides a comparison of human movement between normal and pathological conditions as well as clinical implications for understanding the underlying mechanisms of the movement disorders
- Systematically addresses each body region in functional and dysfunctional kinesiological terms

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